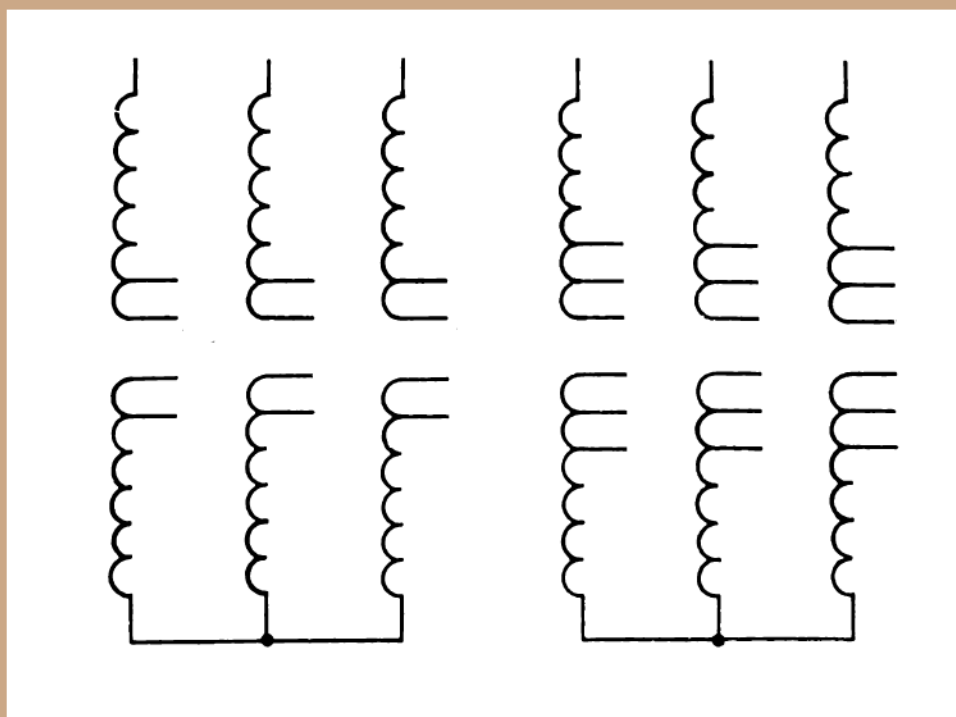


A. DYM KOV

TRANSFORMER DESIGN



MIR PUBLISHERS MOSCOW



TRANSFORMER DESIGN

A. DYMKOV

TRANSLATED FROM
THE RUSSIAN

BY

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MOSCOW

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The Greek Alphabet

A α	Alpha	I ι	Iota	P ρ	Rho
B β	Beta	K κ	Kappa	Σ σ	Sigma
Γ γ	Gamma	Λ λ	Lambda	T τ	Tau
Δ δ	Delta	Μ μ	Mu	Υ υ	Upsilon
E ε	Epsilon	N ν	Nu	Φ φ	Phi
Z ζ	Zeta	Ξ ξ	Xi	X χ	Chi
Η η	Eta	O ο	Omicron	Ψ ψ	Psi
Θ θ	Theta	Π π	Pi	Ω ω	Omega

На английском языке

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Contents

INTRODUCTION	11
1. Contribution of Russian Scientists to Transformer Engineering	11
2. History of National Transformer Building	12
3. Uses of Transformer in Power-Distribution Networks	14
Chapter One. POWER TRANSFORMERS. GENERAL DESIGN CONSIDERATIONS	17
1.1. Transformer Theory and Basic Components	17
1.2. General Design Features	20
1.3. Basic Transformer Materials	26
1.4. Transformer Capacity <i>versus</i> its Size, Weight, Losses and Other Factors	28
1.5. Classification, Standard Sizes and Types	29
Chapter Two. BASIC REQUIREMENTS FOR POWER TRANSFORMER DESIGN	33
2.1. Main Design Parameters	33
2.2. Ratings and Tolerances	33
2.3. Types and Groups of Winding Connection	38
2.4. Choice of Basic Core Sizes	41
2.5. Proportionality Theory and Determination of Basic Core Dimensions	42
Chapter Three. MAGNETIC CIRCUIT COMPUTATIONS	45
3.1. Calculation of the Diameter, Cross Section, Number of Steps of the Core Leg and Yoke, and the Space Factor	45
3.2. Determination of Core Weight	47
3.3. Calculation of Windings, Currents, Number of Turns and Selection of Wire Gauge	50
3.4. Selection of HV and LV Windings and Insulation Gaps. Distribution of Turns in Core Window. Determination of Axial and Radial Winding Structure	53
Chapter Four. COMPUTATION OF OPEN-CIRCUIT CONDITIONS OF TRANSFORMER	59
4.1. Open-Circuit Characteristics According to Standards. No-Load Current and Open-Circuit Losses	59

4.2. Transformation Ratio	60
4.3. Open-Circuit Losses	60
4.4. No-Load Current	62
4.5. Resistive and Reactive Components of No-Load Current	65
4.6. No-Load Current and Open-Circuit Losses as Functions of Primary Voltage	66
4.7. Phasor Diagram and EMF Balance Equation of No-Load Transformer	66
Chapter Five. CALCULATION OF TRANSFORMER LOAD CONDITIONS	69
5.1. On-Load Service Parameters. Impedance Voltage and Short-Circuit Losses	69
5.2. Short-Circuit Losses	71
5.3. Extra (Stray) Losses and Losses in Leads and Taps	72
5.4. Leakage Fluxes in a Loaded Transformer	75
5.5. Determination of Reactance Voltage Drop	77
5.6. Impedance Voltage	82
Chapter Six. VOLTAGE REGULATION AND EFFICIENCY	85
6.1. Computation of Voltage Regulation	85
6.2. Transformer Output Voltage Regulation Characteristic	90
6.3. Efficiency	91
6.4. Conditions for Obtaining the Highest Efficiency	93
Chapter Seven. ADDITIONAL MAGNETIC FLUX LEAKAGE AND MECHANICAL STRESSES	96
7.1. Nonuniform Distribution of Magnetizing Forces	96
7.2. Calculation of Additional Reactance Drop Caused by Transverse Leakage Flux	98
7.3. Mechanical Stresses	100
7.4. Calculation of Radial and Axial Mechanical Stresses	102
Chapter Eight. CALCULATION OF SPECIAL TRANSFORMERS	105
8.1. Autotransformers. Distribution of Currents Through Winding Branches. Standard Capacity	105
8.2. Arrangement of Autotransformer Windings on Core Legs	109
8.3. Three-Phase Autotransformers	110
8.4. Three-Winding Transformers. Basic Data. No-Load Conditions	112
8.5. On-Load Conditions of Three-Winding Transformers. Calculation of Short-Circuit Losses and Impedance Voltage	115
8.6. Calculation of Voltage Drops in Windings of Three-Winding Transformer	116
8.7. Calculation of Regulation and Efficiency with Different Distribution of Load Between Secondaries of Three-Winding Transformer	118

8.8. Design of Transformers Used for Feeding Mercury Rectifiers	122
8.9. Single- and Poly-Phase Rectification Circuits Employing Mercury-Arc Rectifier and Transformer	123
8.10. Determination of Mean Rectified Voltage	128
8.11. Standard kVA Rating of Mercury-Arc Rectifier Transformers	129
8.12. Smoothing Filters	131
Chapter Nine. TAP CHANGING	133
9.1. General Requirements for Transformer Voltage Control	133
9.2. Off-Circuit Tap Changing	134
9.3. On-Load Tap Changing. Equipment Used	136
9.4. Tap Changer Design and Operation	138
9.5. Determination of Resistances of Current-Limiting Reactors and Resistors	147
9.6. On-Load Stepless Voltage Regulators	148
Chapter Ten. THERMAL PROPERTIES AND HEAT EFFECTS	151
10.1. Effects of Heat on Transformer Materials	151
10.2. Overheating Limits and Temperature Measurement	152
10.3. Heat Flow	154
10.4. Calculation of Steady Rise of Winding Temperature Over Oil Temperature	158
10.5. Calculation of Steady Rise of Oil Temperature Over the Ambient	162
10.6. Cooling of Oil-Immersed Transformers. Determination of Tank Size and Surface Area	164
10.7. Transient Heating	172
Chapter Eleven. MAGNETIC CORES. TYPES AND CONSTRUCTION	175
11.1. Electrical Steel	175
11.2. Core Types of Single- and Three-Phase Transformer	177
11.3. Butt-Joint and Interleaved Core Assemblies	180
11.4. Patterns of Interleaving Single- and Three-Phase Magnetic Circuits	182
11.5. Effects of Types of Interleaving and Air Gap Sizes on No-Load Characteristics	183
Chapter Twelve. TYPES AND CONSTRUCTION OF WINDINGS	186
12.1. General	186
12.2. Conductor Material and Types of Windings	187
12.3. Hand of Coil Turns	188
12.4. Cylindrical Layer Winding	190
12.5. Coil-Type Layer Winding	194

12.6. Disc and Continuous Windings	195
12.7. Helical Simplex and Duplex Windings	198
12.8. Arrangement of Transpositions in Helical Winding	200
12.9. Examples of Calculating Equally Distributed Transposition	203
 Chapter Thirteen. INSULATION AND LIGHTNING PROTECTION OF TRANSFORMERS	 205
13.1. Level of Voltages and Overvoltages Under Service Conditions	205
13.2. Requirements for Insulation Strength	206
13.3. Insulation Tests and Test Voltages	207
13.4. Effect of Flashover Voltages on Insulation	210
13.5. Protection of Power Transformers Rated up to 35 kV	216
13.6. Capacitive Neutralization of Transformers Rated at 110 kV and Above	216
13.7. Internal Capacitive Equalization of Inner Windings	219
13.8. Layer Windings	220
13.9. Choice of Correct Size of External and Internal Insulation of Power Transformer	222
 Chapter Fourteen. DESIGN OF TRANSFORMERS	 229
14.1. General Considerations	229
14.2. Core Construction. Cross Section of Core Legs and Yokes. Steel Stamping. Clamping of Core Laminations. Cold-Rolled Steel Cores. Banding	230
14.3. Securing the Windings. Core and Yoke Levelling Insulation	235
14.4. Construction of Power Transformer Tanks. Tank Shapes and Sizes. Tubular Tanks. Finned (Radiator) Tanks. Calculation of Tank Mechanical Strength. Design and Construction of Oil Conservators	237
14.5. Auxiliary Protective Devices	243
14.6. Terminals of Oil-Filled Transformers. Construction of Bushings for 0.5 to 110 kV. Bus Connections	246
14.7. Switches and Taps	250
 Chapter Fifteen. TESTING AND INSTALLATION OF TRANSFORMERS AND DIRECTIONS FOR USE	 257
15.1. Acceptance and Type Tests. Testing the Tanks	257
15.2. Transportation, Storage and Installation	267
15.3. Basic Safety Regulations	269
15.4. Load Capacity	270
15.5. Fault-Finding Chart	271
 Chapter Sixteen. TRANSFORMER ECONOMY	 273
16.1. Elements of Transformer Cost	273
16.2. Calculation of Economic Effectiveness	276

Chapter Seventeen. CURRENT TRENDS OF TRANSFORMER BUILDING IN THE USSR	278
Chapter Eighteen. COURSE DESIGN PROJECTS	282
18.1. Assignment for Design Project of Oil-Cooled Power Transformer Rated at 3 to 35 kV	282
18.2. Examples of Course Project Assignment	283
18.3. 1000-kVA, 10-kV Transformer Core Calculation	284
18.4. Calculation of Heat Flow of 1000-kVA Transformer	296
18.5. Calculation of Mechanical Stresses in Windings of 1000 kVA-Transformer	299
18.6. Electromagnetic Calculation of 2500-kVA, 35-kV Transformer	301
18.7. Calculation of Heat Flow of 2500-kVA Transformer	311
18.8. Calculation of Mechanical Stresses in the Windings of 2500-kVA Transformer	314
18.9. Graphical Representation of the Course Design Project	315
REFERENCES	321
INDEX	322

Introduction

1. Contribution of Russian Scientists to Transformer Engineering

The development of electrical engineering was originally based on the application of direct current. However, direct current, notwithstanding its many advantages, could not satisfy the demands of rapidly growing industry for transmission of high powers over large distances because of difficulties encountered in obtaining high DC power and transmitting it over long lines by way of transformation. High-power transmission was impracticable since it was impossible to increase the DC generator voltage above a definite limit and thus avoid heavy losses of energy in the line. Besides, direct use of DC would be impossible in a number of occasions, for example, for lighting purposes due to electrical hazards involved.

Therefore, electrical engineers focused their attention on practical application and transformation of alternating current, in which field the contribution of the Russian scientists and engineers of the previous century is most remarkable.

The pioneer in transformer building was the Russian scientist P. Yablochkov who, in 1877, built a system with series-connected inductance coils, the secondary windings of which fed the lamps, "Yablochkov candles", of his own invention. The inductance coils actually represented a transformer.

The transformer was further improved by the Russian scientist N. Usagin (1882) and German engineer M. Deri (1885).

The next stage in the application of alternating current systems was marked with the invention of a three-phase AC

system (1889) and a three-phase transformer (1891) by the Russian electrical engineer M. Dolivo-Dobrovolsky.

This and the other discoveries concerning the three-phase electric motor and AC transformation gave a tremendous impetus to the wide use of electric power in industry and manufacture of increasingly larger transformers in power and voltage.

The first transformer rated at 30 kV was built as early as 1891. This was also the first oil-cooled transformer. Further on, the rise in voltages progressed as follows: a 110-kV transformer built in 1907; 150-kV, in 1912; 220-kV, in 1921; 287.5-kV, in 1937; 400-kV, in 1952, and 500-kV transformer, in 1958. As for the transformer power capacity, the characteristic figures are: 2250 kVA in 1901; 8300 kVA in 1921; 16,700 kVA in 1922; 90,000 kVA in 1955, and 240,000 kVA in 1959. The transformers under design now will have power capacity up to 1,000,000 kVA (1000 MVA) at a service voltage of 750 to 1200 kV.

2. History of National Transformer Building

In pre-revolutionary Russia the transformer building industry was insignificant. The plants operating in Kharkov, Petrograd, and Moscow were engaged in assembly of transformers to the drawings of foreign manufacturers. At that time the power per unit was not more than 2000 kVA.

In Soviet Russia, the transformer building industry rapidly developed concurrent with the development of other industries of the national economy. Thus, in 1924 the Kharkov electrical machine building factory started manufacturing transformers of 12 500 kVA, 40 kV.

Intensive development of the transformer manufacturing industry began from 1927 with the construction, by the government's decision, of the "Electrozavod" in Moscow — the electrical-machine manufacturing plant.

Since 1953, new transformer-building works have been commissioned of which the largest, the Zaporozhye plant, produced in 1965 transformers with a total power capacity of 45 GVA (G is a fractional unit equal to 10^9).

The first Soviet-made transformer rated at 110 kV was built in 1931 and a 220-kV transformer, in 1933, at the Moscow "Electrozavod". In 1955, the Zaporozhye plant built a single-phase transformer of 90 MVA capacity and in 1956, a 123.5-MVA, 400-kV, transformer designed for the Kuybyshev-Moscow power transmission line. The transformers built in subsequent years were: a 135-MVA, 500-kV, and a 240-MVA, 220 kV, three-phase transformer, in 1959; a 630-MVA, 220-kV, three-phase, and a 417-MVA, 750-kV, single-phase autotransformer designed for an experimental transmission line from the Konakovo hydroelectric power plant to Moscow, in 1967; a 417-MVA, 500-kV, single-phase transformer, in 1968, and a 400-MVA, 500-kV, three-phase transformer, in 1969.

Besides, the tropicalised versions of single-phase transformers of 167 MVA, 500 kV, and three-phase transformers of 206 MVA, 500 kV were built to be erected on the Aswan hydroelectric plant, Egypt.

Large and, in a number of cases, medium transformers should be provided with on-load tap-changing equipment to avoid interruption of power supply when changing voltage steps.

Development of HV transmission lines accentuated the problem of protecting transformers against lightning and switching surges. Eventually, the electrostatic shielding of transformers was designed and embodied in all manufactured transformers of 110 kV and more. These are known as the lightning-proof transformers.

Apart from the power transformers, there is a varied assortment of special transformers such as the electric arc furnace, traction, mercury rectifier, instrument, test transformers and the like.

Concurrent with the construction of transformer-building plants, new works have been put into manufactured operation and the existing ones expanded for the production of transformer materials, such as electrical alloy steel, winding wire, insulating pressboard, porcelain bushings, transformer oil, etc.

3. Uses of Transformer in Power-Distribution Networks

At the present time the electric power for industrial and utility purposes is generated by large hydraulic power plants and steam power stations in the form of a three-phase AC system of 50 Hz (60 Hz in the USA).

The voltages of the generators installed at the power plants are standardized and according to the national standard specifications may be: 6600, 11,000, 13,800, 15,700, 18,000 or 22,000 V. To transmit the electric power over long routes this voltage should be increased to 110, 220, 330 or 500 kV depending on the route covered and power transmitted.

On the contrary, this voltage should be decreased by the distribution substations to 6 or 10 kV (in urban areas and industrial centres) or to 35 kV (in rural areas and in the case of great extents of distribution networks). And, ultimately, the voltage used in industrial and domestic premises should be dropped to 380, 220 or 127 V. Under certain circumstances as, for instance, in lighting the boiler rooms, mechanical workshops and damp premises, the voltage should be further lowered to a safe value of 12, 24 or 36 V.

The purpose of raising or lowering the AC supply voltages is accomplished by power transformers.

Transformers do not produce power; their sole purpose is to transform or change the voltage value. In this application they may behave as step-up transformers, if designed to raise voltage, or step-down transformers, if they are intended to lower voltage. But basically each transformer may be used as both the step-up and the step-down transformer because it is a reversible machine.

The power transformers exhibit a remarkably high efficiency running from 95 to 99.5 per cent, depending on the power capacity. The greater the power capacity of the transformer, the higher its efficiency.

As is apparent from Fig. 1 which gives an example of a distribution line the energy transmitted from the sending station to the receiving station undergoes several stages of transformation. Therefore, the load demand (the total power of all the transformers installed in the line) should be several times as much as that of the sending-station generators.

Besides, the step-down transformers used in the distribution line have an average load about 50 per cent of their rated power. An example of the daily load chart of the power transformer is shown in Fig. 2.

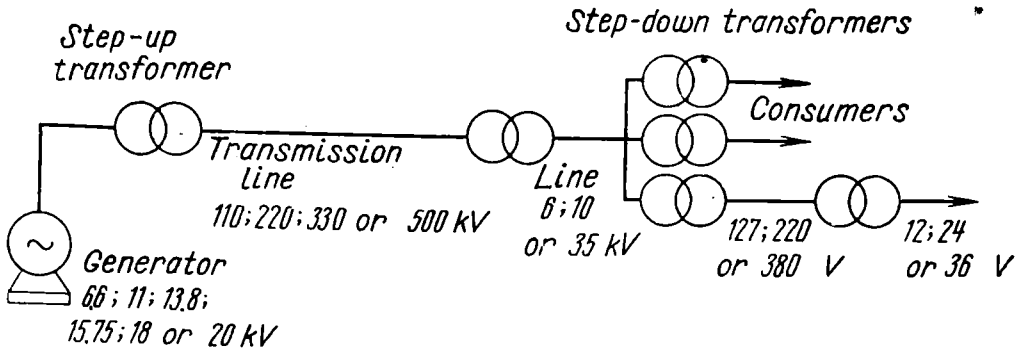


Fig. 1. Example of transmission and distribution of electric power

Owing to the two reasons stated above, that is, multiple transformation and variation in the magnitudes of loads, the total load demand of the power transformers is practically

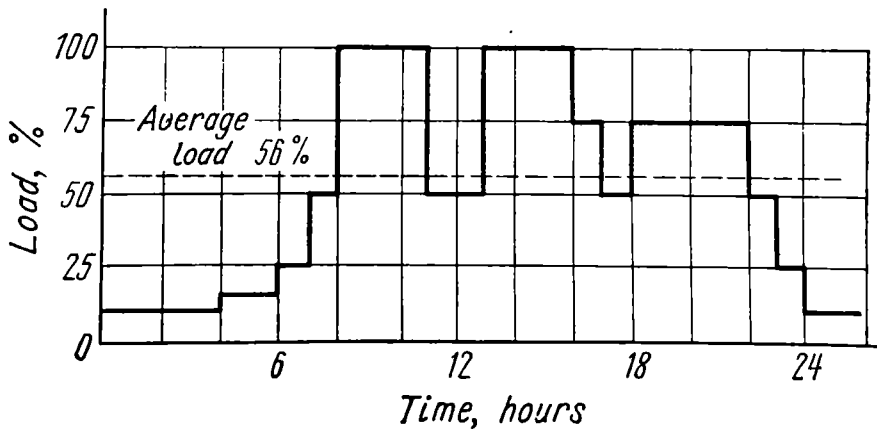


Fig. 2. Daily load chart of power transformer

7 to 8 times as great as the power of the sending-station generators.

The foregoing exposes an exceedingly important role the transformers play in transmission and distribution of electric power. But for the transformers, the idea of long-distance transmission of power, in the way it is practised nowadays, would have been inconceivable.

Review Questions

1. Give the names of Russian scientists of the 19th century who pioneered the application of transformers.
2. Name the greatest power capacity and service voltages of transformers now in use.
3. What are the functions of a transformer in transmission and distribution of electric power?
4. What is the load demand and its magnitude?

Chapter One

Power Transformers. General Design Considerations

1.1. Transformer Theory and Basic Components

A *transformer* is a static electromagnetic device which transforms electrical energy from one or more (primary) AC circuits to one or more (secondary) AC circuits with the changed values of voltage and current.

The transformer behaviour is based on Faraday's law of electromagnetic induction. The electromagnetic induction is the production of electromotive force (EMF) and induced current in a closed conducting circuit by a change in the magnetic flux linking with that circuit.

The instantaneous value of EMF induced in the circuit is defined as

$$e = -\frac{d\Phi}{dt} V \quad (1.1)$$

where e = instantaneous EMF value

Φ = magnetic flux in webers, Wb

The negative sign (—) in Eq. 1.1 is placed according to Lenz's law which states that the current induced in a circuit due to a change in the magnetic flux produces a secondary magnetic flux so directed as to *oppose* the change in the initial flux.

Equation 1.1 indicates that the induced EMF is independent of the effective value of magnetic flux Φ , depending only on the rate of change of this flux. Furthermore, the EMF induced in the circuit depends neither on the current through the circuit nor on the circuit impedance.

If there are a few series-connected turns N in a circuit, then the EMF induced in the coil thus formed will be N

times greater, that is,

$$e = -N \frac{d\Phi}{dt} \quad V \quad (1.2)$$

Should we take two coils *I* and *II* with a number of turns N_1 and N_2 and arrange them coaxially, we shall obtain a transformer in its simplest form. This elementary transformer shown in Fig. 1.1. functions as follows.

Coil *I* called the *primary* is fed with the AC voltage of effective value V_1 . Consequently, electric current is induced

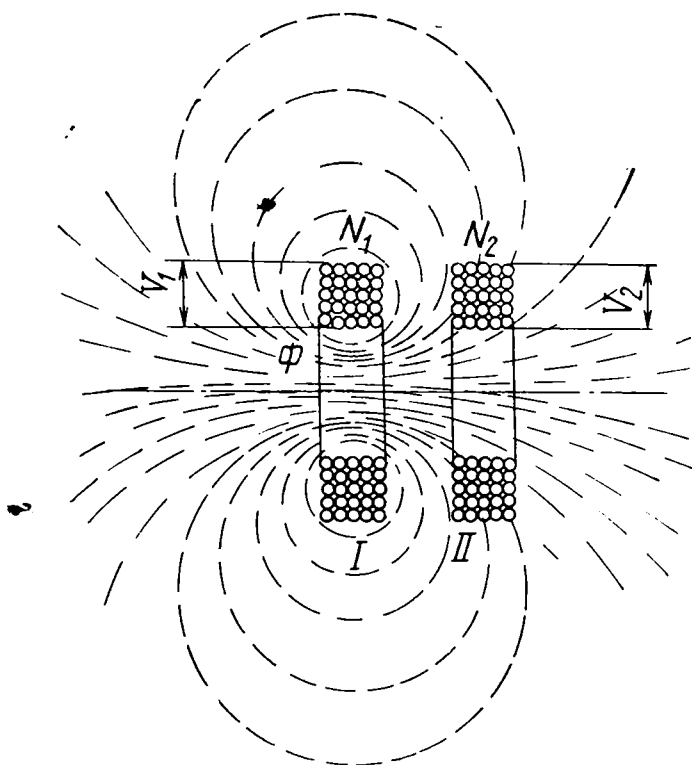


Fig. 1.1. Elementary transformer (without magnetic core)

in the circuit which, in its turn, produces alternating flux Φ . The magnetic lines of force of this flux cut not only the primary coil but also *secondary* coil *II*. Therefore, self-inductance EMF (E_1) is induced in the primary and mutual inductance EMF (E_2) in the secondary coil (E_1 and E_2 are the effective EMF values).

Electromotive force E_1 is compensated for by the applied primary voltage V_1 . Electromotive force E_2 represents secondary voltage V_2 (neglecting the voltage drops).

However, the transformer illustrated in Fig. 1.1 is not suitable for practical use. The magnetic flux here is small

due to a high air resistance and, therefore, the link coupling between the coils is loose. Besides, a certain portion of the flux lines does not cut the secondary, forming therewith a *leakage flux* which does not contribute to voltage transformation; as a result the secondary voltage lowers.

To reduce resistance on the path of the magnetic flux and thus increase the link coupling between the primary and

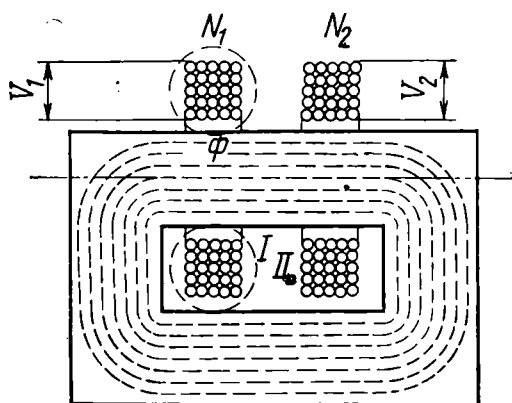


Fig. 1.2. Transformer principle (two windings on a closed steel core)

secondary coils, known as windings, the latter should be arranged on a closed iron (steel) core (magnetic circuit) as is shown in Fig. 1.2.

The use of a closed magnetic steel core greatly reduces the relative value of leakage flux because permeability of the transformer steel is 800 to 1000 times higher than that of air (or any diamagnetic material).

Hence, two or more windings placed on a closed magnetic core represent a *transformer*.

From this it becomes obvious that the principal parts of a transformer are the primary and secondary windings and the magnetic core.

Assuming that both the primary and the secondary are threaded by one and the same magnetic flux (neglecting the leakage flux), we can write by Eq. 1.2:

$$e_1 = -N_1 \frac{d\Phi}{dt}$$

$$e_2 = -N_2 \frac{d\Phi}{dt}$$

Dividing one equation by the other easily gives

$$\frac{e_1}{e_2} = \frac{N_1}{N_2}$$

Because $e = \sqrt{2} E \sin \omega t$ (E is the effective value of EMF), it can be written that

$$\frac{e_1}{e_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = K \quad (1.3)$$

where K is the transformation ratio of a transformer.

The *transformation ratio* is the ratio of the values of electromotive forces induced correspondingly in the primary and secondary windings equalling the ratio of the numbers of turns in these windings.

1.2. General Design Features

As it has been already stated, the transformer consists basically of a magnetic circuit (core) on which the windings are placed. Besides, the transformer comprises a number of constituent parts and elements designed mainly to facilitate the transformer use and maintenance. These parts and elements are various insulators used for insulation of current-carrying parts, bushings and leads connecting the windings to transmission lines; switchgear for the transformer voltage adjustment; transformer oil tanks; transformer cooling tubes and radiators, etc.

The transformer magnetic core is actually a closed magnetic circuit which serves as a passage for the main magnetic flux linking both windings.

Power transformers are mainly designed with the leg-type cores. Single-phase transformers have two-legged cores and the three-phase transformers are provided with three-legged cores. The cores are connected by means of the upper and lower yokes. The core-type single-phase and three-phase transformers are shown in Fig. 1.3 and 1.4.

The magnetic core of a transformer is assembled from the laminations of the electrical steel sheets 0.35 or 0.5 mm thick. To reduce eddy current losses, the laminations are separated with insulating varnish or a suitable insulating film.

When the cores are assembled from square laminations, the *interleaved construction* is employed. In this case the

joints of one layer are overlapped by laminations of the adjacent layer, as is shown in Fig. 1.5b for the single-phase transformers and in Fig. 11.6b for the three-phase transformers.

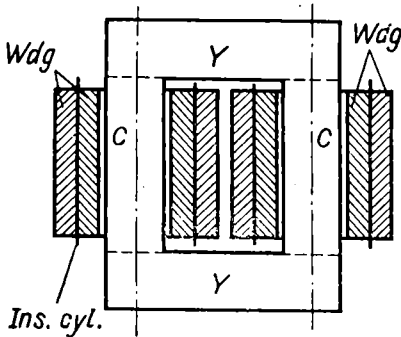


Fig. 1.3. Single-phase core-type transformer

C—core; *Wdg*—winding; *Ins. cyl.*—insulation cylinder; *Y*—yoke

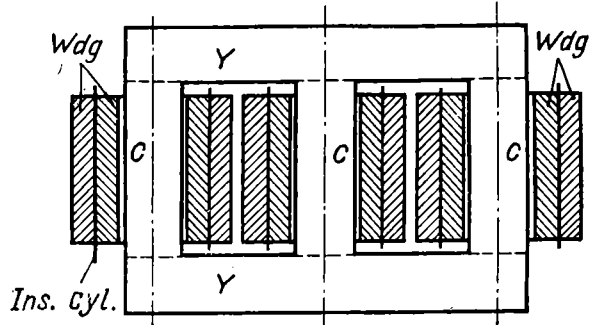


Fig. 1.4. Three-phase core-type transformer

The butt-joint assembly (Fig. 1.5a) is infrequent.

The laminated-interleaved construction has a double advantage, one being the reduction of the transformer magne

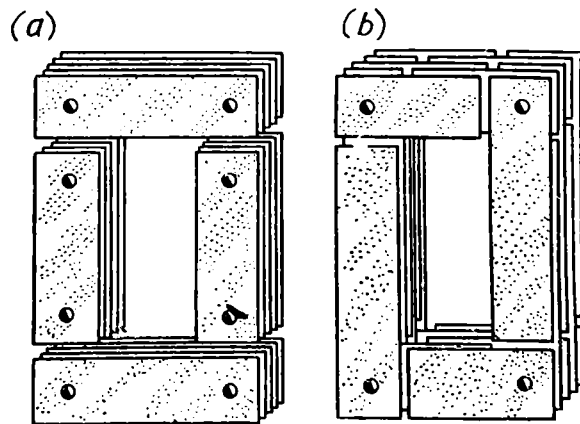


Fig. 1.5. Core assemblies
(a) butt-joint assembly; (b) interleaved assembly

tizing current and the other being the increase in the mechanical strength of the magnetic core assembly.

The core legs which carry the windings have a stepped section conforming to a circle, such as shown in Fig. 1.6. The number of steps depends on the transformer rating: the greater the power (and hence the core-circle diameter), the more steps are chosen (see Table 14.1).

To improve the removal of heat produced by steel losses, large transformers are provided with cooling ducts used for circulation of oil or air (in dry-type transformers).

The core yoke has also a stepped section. However, for the sake of simplicity of the low-power transformer design, the number of steps in the yoke is often chosen to be less than that in the core leg or, occasionally, a square-section yoke is fabricated. For the no-load current and steel losses to be

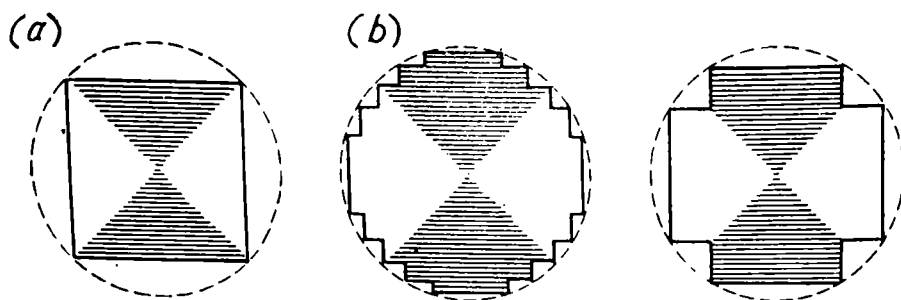


Fig. 1.6. Core cross section
(a) rectangular; (b) stepped

reduced in the low-power transformers, the yoke section is usually chosen to be 5 to 10 per cent greater than that of the leg.

The core design and construction are covered in more detail in Chapter Eleven.

It is usual to term the windings of the power transformers as the *HV and LV windings*, rather than the primary and secondary, because either of them may serve as the primary or secondary, depending on which of them is connected to the supply network.

The transformer winding forms a part of the electric circuit (be it primary or secondary) and as such it consists of conducting material (winding copper or aluminium) and insulating elements. The winding set embraces also the terminals, voltage-changing taps, capacitive protection rings and electrostatic shields providing electrostatic shielding protection against voltage surges.

An arrangement of the HV and LV windings on the core leg is mostly concentric, that is, one of the windings is placed over (or wound around) the other one, as is shown in Fig. 1.7a. The LV winding is usually placed next to the core

leg because it is easier to isolate this winding from the core on account of its low voltage, than the HV winding. The insulation spacers in the form of cylinders are interposed between the windings (see Fig. 1.3). In the case of a concentric arrangement, cylinder-shaped two- or multi-layer, coil-type, helical or continuous windings are usually employed.

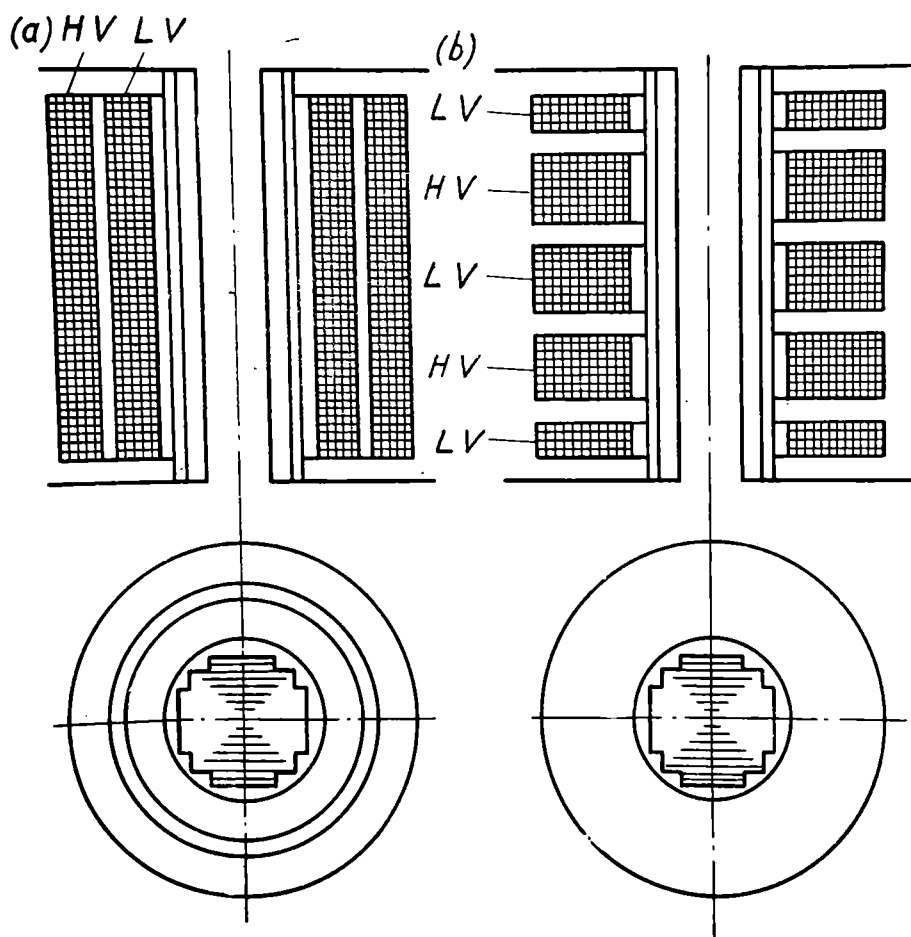


Fig. 1.7. Arrangement of HV and LV windings on the magnetic core
(a) concentric winding; (b) sandwich winding

The proper choice of the winding type is determined by the number of turns, size and number of parallel conductors, way of cooling, transformer power and other factors.

The winding design and arrangement will be discussed in greater detail in Chapter Twelve.

Some of the special transformers, for example, electric arc furnace transformers make use of sandwich windings. In

such an arrangement the disc windings consisting of single- or double-disc coils are employed. The HV and LV coils are sandwiched on the core, with the LV coils placed next to the yoke as they require shorter insulating gaps. The sandwi-

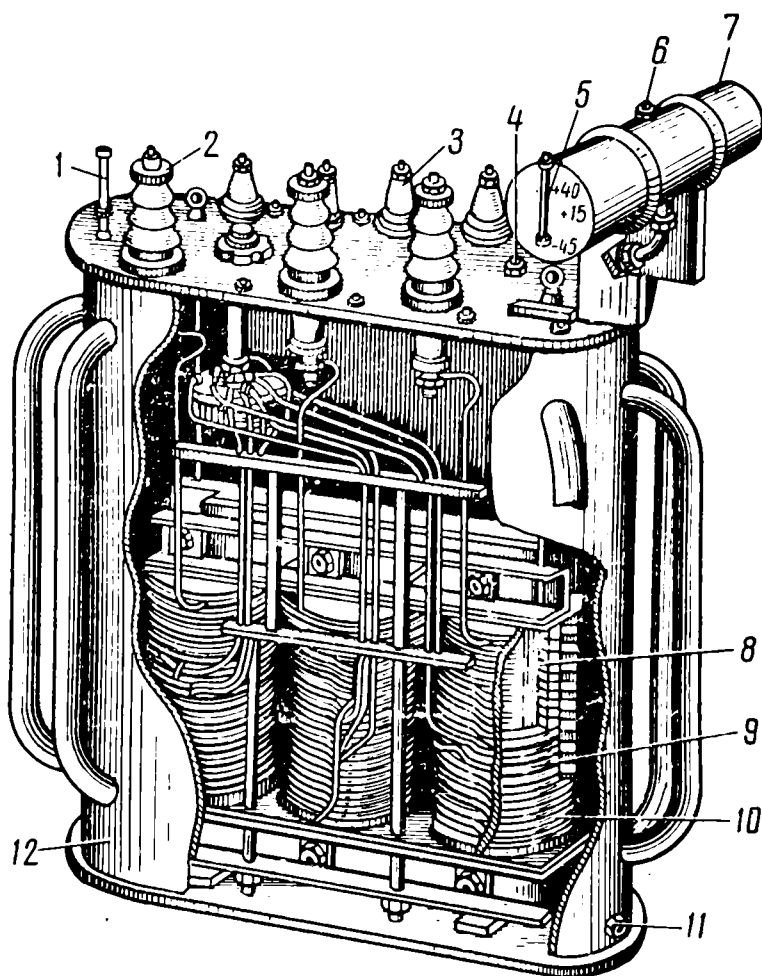


Fig. 1.8. General view of 320-kVA, 6-kV, oil-filled, three-phase power transformer with the tubular tank

1—thermometer; 2—HV bushing; 3—LV bushing; 4—oil-filling plug; 5—oil-level indicator; 6—oil-replenishment plug; 7—oil conservator; 8—magnetic core; 9—LV winding; 10—HV winding; 11—oil sampling and drain plug; 12—oil tank

ched winding construction is schematically shown in Fig. 1.7b.

The magnetic core with the windings and fasteners constitute the working parts of a power transformer.

The losses occurring in the operating transformer are converted into heat. To avoid overheating of the transformer

(mainly it refers to its insulation) the transformer windings and magnetic core should be provided with adequate cooling facilities.

In the majority of cases, the transformer working parts are enclosed in a tank filled with transformer oil. The oil, when heated, begins to circulate, giving up its heat to the tank walls wherefrom the heat is dissipated into the surrounding air.

• To increase the radiating surface of the tank, which is essential to large-size transformers, the tanks are manufactured with the tubes welded into the walls.

Large-capacity transformers are provided with cooling radiators or other cooling arrangements.

A general view of the power transformer with a tubular tank is shown in Fig. 1.8.

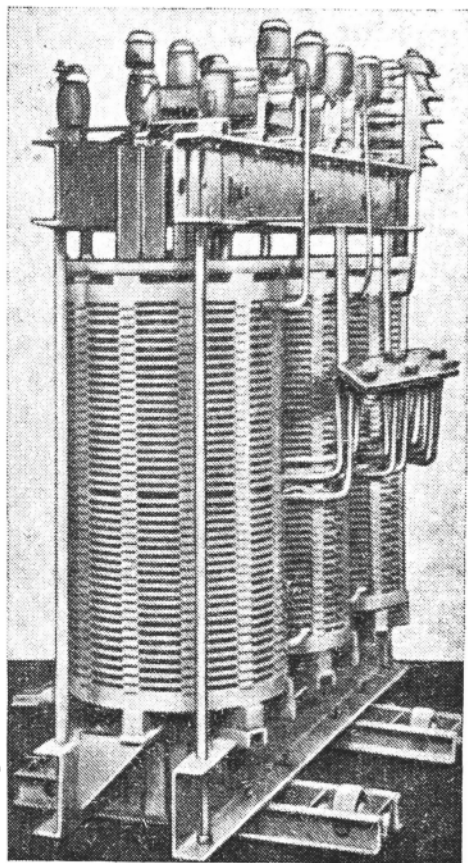


Fig. 1.9. 500-kVA, 10-kV, three-phase, air-cooled transformer with casing removed

In more detail the cooling problems and appropriate cooling equipment are discussed in Chapter Ten.

Recently, the air cooling of the power transformer has found more extensive application due to the development and introduction of heat-resistant insulants. Thus, it has been made possible to manufacture air-cooled transformers of 1000 kVA and up to 15 kV.

A general view of the air-cooled transformer with a casing removed is shown in Fig. 1.9.

1.3. Basic Transformer Materials

The materials required for the manufacture of transformers may be divided into ferromagnetic and conducting materials, such as magnetic-core electrical steel and winding wires; electrical insulation materials, such as insulation pressboard, cable and telephone cable paper, varnished cambric, pertinax, porcelain, transformer oil, etc., needed for insulation of windings and other current-carrying parts of a transformer, and constructional materials used for manufacturing the parts of a transformer framework, tanks, cooling devices, various fasteners, etc.

The magnetic cores are made from thin sheets of hot- or cold-rolled alloyed electrical-grade steel.

Hot-rolled steel originally used in the industry allowed an increase in the magnetic induction B of up to 1.4 or 1.45 teslas (T). Though the quality of this steel as regards the reduction of specific losses was gradually improved, it was nevertheless superseded by cold-rolled, grain-oriented steel with specific losses 1.5 to 2 times as low as those of hot-rolled steel and with much greater permeability. Cold-rolled steel permits of increasing induction up to 1.6 to 1.7 teslas.

The decrease in steel losses is instrumental for saving the ferromagnetic conducting and constructional materials, thus reducing the transformer cost and increasing the transformer efficiency.

One of the basic materials used for the manufacture of transformer windings is the winding copper (or aluminium) fabricated as an insulated round or rectangular conductor. For conductor sizes, refer to paragraph 12.2.

The insulating materials used in transformers should possess definite properties, of which the most essential are the electrical and mechanical strength, moisture and heat resistance.

Insulating pressboard 0.5 to 3 mm thick is a most commonly used insulant in the transformers. This material exhibits adequate dielectric properties, mechanical strength and is a good oil absorbent. This material is used for manufacturing various insulation elements (refer to Chapters Twelve to Fourteen).

The cable paper 0.12 mm thick is suitable as the winding interlayer insulation and is also used to insulate the winding ends and leads.

Varnished silk and cotton are used for insulation of winding ends and leads and also for added insulation at such points as, say, soldered wire joints.

Cotton, herringbone, and taffeta tapes are suitable as an auxiliary fastening material and as a means for protecting the insulation.

Bakelite paper cylinders and tubing serve as the winding formers (insulating cylinders) and for insulating the clamping pins of the core legs and leads.

Pertinax sheets up to 50 mm thick are used for manufacturing the insulating strips and boards and switchgear insulating elements.

Porcelain is utilized for the production of bushing insulators and some insulating elements of the air-cooled transformers.

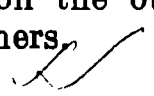
Varnishes and enamels also belong to insulating materials. Oil baking varnishes are used for coating magnetic core laminations, glyptal baking varnishes for impregnating the windings of oil-filled transformers and asphalt varnishes for impregnating the windings of dry-type transformers.

The windings and other parts of the dry-type transformer operating in the conditions of excessive humidity are coated with special varnishes and enamels capable of forming a sturdy moisture-resistant film.

It should be noted that in view of the modern, rigid construction of the windings in oil-filled transformers, a number of manufacturers discarded the impregnation practice altogether (this is discussed in detail in Ch. Seventeen).

Transformer oil serves a dual purpose: it facilitates the removal of heat from the core and windings and, at the same time, improves the dielectric strength of a transformer.

The use of transformer oil made it possible, on the one hand, to increase the electromagnetic loads (induction and current density) on the ferromagnetic and conducting materials, reducing thereby their expenditure and, on the other, to build more powerful high-voltage transformers.



1.4. Transformer Capacity *versus* its Size, Weight, Power Losses and Other Factors

A properly designed transformer, apart from the fact that it should meet certain technical requirements, must be inexpensive. The cost of a transformer depends on its size and weight and, primarily, on the weight of the ferromagnetic and conducting materials as the most costly ones.

The weight of the ferromagnetic materials is influenced, in the end, by the size of the magnetic circuit.

To choose the principal sizes of the magnetic circuit, it is necessary first to disclose the relationship between these sizes and the rated power P of the transformer. As we shall see, the linear dimensions rise with the transformer power.

To determine the relationship between the sizes and power, we should assume that transformers of different ratings must be geometrically similar, i.e., the ratios of the three linear sizes must be proportionally equal, and that the electromagnetic loads on the ferromagnetic and conducting materials, i.e. induction and current density in the windings must also have identical ratios.

The transformer power is

$$P = mVI$$

where m is the number of phases; V and I are the phase voltages and currents (in one of the windings).

Let us recall the fundamental formula of the transformer voltage,

$$E = 4.44 fNBA_{core} \text{ (volts)}$$

Since B is assumed to be constant, it can be easily seen that voltage E is proportional to the cross-sectional area A of the magnetic core leg or to the square of linear dimensions.

$$E \equiv A_{leg} \equiv l^2$$

The current density in the winding is

$$\delta = \frac{I}{s_c}$$

whence $I = \delta s_w$, that is, the current through the winding is proportional to the cross section s_c of the wire conductor

or to the square of linear dimensions:

$$I \equiv s_c \equiv l^2$$

Hence, the transformer power will be proportional to the quadruple of its linear dimensions

$$P \equiv VI \equiv l^2 l^2 \equiv l^4$$

The weight G of ferromagnetic and conducting materials (steel and copper) of the transformer is proportional to their volumes v or to the cubes of their linear dimensions. Hence it follows that the weight of these materials will be proportional to the transformer kVA rating raised to the three-fourth power or,

$$G \equiv v \equiv l^3 \equiv P^{3/4}$$

Practically, it means that the specific losses of ferromagnetic and conducting materials expressed in kg/kVA decrease with an increase in the kVA rating. Therefore, more powerful transformers are relatively less expensive.

In addition, the powerful transformers are more economical in service since their power losses are relatively smaller and, consequently, their efficiency is higher. This is so because the transformer power losses including the open-circuit losses P_o and short-circuit losses P_{sc} (at invariable values of B and δ of electromagnetic loads on the ferromagnetic and conducting materials) are proportional to the weight of the ferromagnetic and conducting materials, i.e.,

$$P_o \equiv B^2 G_{st} \text{ and } P_{sc} \equiv \delta^2 G_w$$

where G_{st} = weight of the ferromagnetic steel

G_w = weight of the winding wire

As the weight of the materials grows at a slower rate with the rise in power, the increase in losses is also slow and, thus, the transformer efficiency rises.

1.5. Classification, Standard Sizes and Types

The general-purpose power transformers are conventionally divided into groups or sizes according to their voltage rating and power capacity. Thus, transformers with 25 to

100 rated kVA belong to size I; those with 160 to 630 kVA are grouped under size II; 1000 to 6300-kVA transformers belong to size III; transformers rated at 10,000 kVA and above with a circuit voltage of 35 kV and all transformers with an HV winding voltage of 110 kV are classified under size IV; transformers of 40,000 kVA and above with an HV winding voltage of 220 kV and above belong to size V; and those of 100,000 kVA and above belong to size VI. The above-listed transformers are usually of the oil-immersion design, that is, the active parts are immersed in an oil tank to enhance cooling and increase insulation strength. However the transformers of 1000 to 1600 kVA and 10 to 15 kV may also be of the air-cooled design. The transformer cooling system is covered by the coded type designation.

Designations of the transformer type consist of letters and figures. The first letter *T* or *O* denotes the number of phases (*T*, three-phase and *O*, single-phase transformer). Occasionally the designation of special-purpose transformers includes a letter, standing ahead of the phase-code letter and indicating the transformer application. Thus, letter *Ɖ* specifies the electric-furnace transformer; letter *A* denotes the auto-transformer.

The second letter (or two letters) which follows letter *T* or *O* indicates the cooling system: *M*—oil-immersed, self-cooling; *Δ*—oil-immersed, forced-air and self-oil cooling; *ΔΔ*—oil-immersed, forced-air and forced-oil cooling; *ΔΔ*—oil-immersed, water- and forced-oil cooling; *H*—self-cooling by circulation of nonflammable liquid dielectric; *C*—natural air cooling for indoor use; *C3*—natural air cooling for outdoor use.

The third letter discloses a specific design feature of the given transformer; *T*—three-winding transformer; *H*—on-load tap changing; *P*—mercury-rectifier supply transformer.

The last letter *F* means lightning protection and indicates that the transformer is provided with electrostatic shielding protection.

It is impossible to list all the letter designations insomuch as an ever growing variety of transformers designed for special application require additional letter codes.

The numerical part of designations consists of two figures. The first figure, numerator, denotes the kVA rating

of the transformer whilst the second figure, denominator, indicates the HV winding voltage in kV.

By way of illustration we shall decode the transformer type designation TДTH-6300/35. This is a three-phase, forced-air-cooled, three-winding transformer with on-load tap changing, rated at 6300 kVA, 35 kV.

The winding leads are connected to the porcelain bushings or terminals installed on the tank cover (or on its wall in the case of the small-capacity and air-cooled transformers).

The standardized terminal marking of the transformer is given below in Table 1.1.

Table 1.1

Winding	Transformer	
	three-phase	single-phase
HV	$O-A-B-C$	$A-X$
LV	$o-a-b-c$	$a-x$
MV	$O_m-A_m-B_m-C_m$	A_m-X_m

The terminals should be arranged in the above-given order if viewed from the HV side.

The basic parameters and technical specifications of the three-phase power transformers should conform to the requirements specified by the appropriate national standards.

The standard kVA ratings of the power transformers are 25, 40, 63, 100, 160, 250, 400, 630, 1000, 1600, 2500, 4000 and 6300 kVA.

The rated line voltages as specified by the appropriate standards are 6000, 10,000, 20,000 and 35,000 V for the HV windings and 230, 400, 690, 3150, 6300, 10,500, 11,000 V for the LV windings.

The winding connections for the HV windings may be

$\Upsilon, \Upsilon, \Delta$ and $\Upsilon, \Delta, \Upsilon$ for the LV windings.

This book covers essentially only three-phase, oil-immersed, two-winding power transformers of sizes I, II and III with the kVA ratings from 25 to 6300 kVA and with the

highest service voltage of 35 kV. Less consideration is given to certain types of special transformers, such as three-winding transformers, mercury-rectifier supply transformers and auto-transformers. Special transformers may be also referred to this or other size, depending on their ratings.

The standard power of a special transformer or power related to its size is regarded to be the power of a two-winding power transformer rated at the same high voltage and with the normal voltage adjustment range ($\pm 5\%$), which can be built up with a magnetic core (model) of the given special transformer. The standard power rating also depends on the auxiliary equipment and apparatus installed in the transformer.

Review Questions

1. Explain the principle of transformer operation.
2. What is the function of the steel core?
3. Define the transformation ratio.
4. What are the basic parts of a transformer?
5. Why is the magnetic core shaped to a stepped cross section?
6. Describe the methods of arranging windings on the transformer core.
7. Name the materials used in the production of transformers.
8. What is the basic parameter that determines the transformer size?
9. Give the classification of transformer power in relation to its size.
10. How are the transformer types designated?
11. How are the winding terminals marked?

Chapter Two

Basic Requirements for Power Transformer Design

2.1. Main Design Parameters

The following are the main parameters which should be specified for calculation of a double-wound power transformer:

- (a) P , kVA, power rating;
- (b) V_1 and V_2 —rated line voltages of the HV and LV windings, in volts;
- (c) m , number of phases;
- (d) f , frequency, Hz;
- (e) type and group of winding connection;
- (f) method of cooling;
- (g) type of duty—long-time or short-time (power transformers are commonly calculated for continuous duty);
- (h) indoor or outdoor installation.

In addition, certain service parameters should also be specified for a transformer being designed. These are:

- (a) P_o , open-circuit losses, W;
- (b) P_{sc} , short-circuit losses, W;
- (c) i_o , no-load current, %;
- (d) V_{sc} , impedance voltage, %.

2.2. Ratings and Tolerances

The main and service parameters are given in the appropriate national standard specifications and only those transformers which meet the requirements of the standards are allowed for series production.

As for the academic design projects carried out by students, the instructor may specify also the parameters other

Table 2.1

Rated, power kVA	Upper limit of HV winding rated voltage, kV	Type and group of connection	Losses, W		Impe- dance vol- tage, %	No- load cur- rent, %
			Open- circuit	Short- circuit		
25	10	$Y/Y-0$	125	600	4.5	3.2
		$Y/\Delta-11$	125	690	4.7	3.2
40	10	$Y/Y-0$	180	880	4.5	3.0
		$Y/\Delta-11$	180	1000	4.7	3.0
63	10	$Y/Y-0$	265	1280	4.5	2.8
		$Y/\Delta-11$	265	1470	4.7	2.8
	20	$Y/Y-0$	290	1280	5.0	2.8
		$Y/\Delta-11$	290	1470	5.3	2.8
	100	$Y/Y-0$	365	1970	4.5	2.6
		$Y/\Delta-11$	365	2270	4.7	2.6
	35	$Y/Y-0$	465	1970	6.5	2.6
		$Y/\Delta-11$	465	2270	6.8	2.6
160	10	$Y/Y-0; Y/\Delta-11$	540	2650	4.5	2.4
		$Y/\Delta-11$	540	3100	4.7	2.4

Continued

Rated power, kVA	Upper limit of HV winding rated voltage, kV	Type and group of connection	Losses, W		Impedance voltage, %	No-load current, %
			Open-circuit	Short-circuit		
160	35	$\Upsilon/\Upsilon - 0; \Upsilon/\Delta - 11$	660	2650	6.5	2.4
		$\Upsilon/\Upsilon - 11$	660	3100	6.8	2.4
250	10	$\Upsilon/\Upsilon - 0; \Upsilon/\Delta - 11$	780	3700	4.5	2.3
		$\Upsilon/\Upsilon - 11$	780	4200	4.7	2.3
	35	$\Upsilon/\Upsilon - 0; \Upsilon/\Delta - 11$	960	3700	6.5	2.3
		$\Upsilon/\Upsilon - 11$	960	4200	6.8	2.3
400	10	$\Upsilon/\Upsilon - 0; \Upsilon/\Delta - 11$	1080	5500	4.5	2.1
		$\Delta/\Upsilon - 11$	1080	5900	4.5	2.1
	35	$\Upsilon/\Upsilon - 0; \Upsilon/\Delta - 11$	1350	5500	6.5	2.1
630	10	$\Upsilon/\Upsilon - 0; \Upsilon/\Delta - 11$	1680	7600	5.5	2.0
		$\Delta/\Upsilon - 11; \Upsilon/\Upsilon - 0$	1680	8500	5.5	2.0
	35	$\Upsilon/\Upsilon - 0; \Upsilon/\Delta - 11$	2000	7600	6.5	2.0

than those given in the standards in order to avoid duplication of the work already done and encourage the students to do independent research.

The standardized rated line voltages of HV and LV windings as well as types and groups of winding connections for separate kVA ratings are presented in Tables 2.1 and 2.2.

A tap changing equipment should be provided at the HV side of the power transformer for changing the transformation ratio in respect to the rated value.

Table 2.2

Rated power, kVA	Upper limits of rated voltages, kV			Losses, W		Impe- dance volta- ge, %	No-load cur- rent, %
	HV	LV		open- circuit	short- circuit		
		off-circuit tap-chan- ging trans- former	on-load tap-chan- ging trans- former				
1000	10	0.69	0.69	2450	12 200	5.5	1.4
	10	10.5	—	2450	11 600	5.5	1.4
	35	0.69	0.69	2750	12 200	6.5	1.5
	35	10.5	11	2750	11 600	6.5	1.5
1600	10	0.69	0.69	3300	18 000	5.5	1.3
	10	6.3	6.3	3300	16 500	5.5	1.3
	35	0.69	0.69	3650	18 000	6.5	1.4
	35	10.5	11	3650	16 500	6.5	1.4
2500	10	0.69	0.69	4600	25 000	5.5	1.0
	10	10.5	6.3	4600	23 500	5.5	1.0
	35	0.69	0.69	5100	25 000	6.5	1.1
	35	10.5	11	5100	23 500	6.5	1.1
4000	10	6.3	6.3	6400	33 500	6.5	0.9
	35	10.5	11	6700	33 500	7.5	1.0
6300	10	10.5	6.3	9000	46 500	6.5	0.8
	35	10.5	11	9400	46 500	7.5	0.9

Note. Short-circuit losses of an on-load tap-changing transformer are allowed to be 10 per cent higher than those given in Table 2.1.

Power transformers employ two kinds of tap changing, *viz.*, the off-circuit tap changing effected after all of the transformer windings are disconnected from the supply network and the on-load tap changing.

The values of the service parameters, such as the open-circuit and short-circuit losses, impedance voltage and no-load current are also indicated in Tables 2.1 and 2.2.

As can be seen from these tables, the open-circuit and short-circuit losses may differ at one and the same load capacity of a transformer.

The open-circuit losses increase with the service voltage because an increase in voltage calls for larger insulation gaps between the windings and the core, which causes an enlargement of the core size and thus results in heavier losses.

The short-circuit losses increase in the case of zigzag connection because of a greater weight of the winding wire. Since the zigzag branches are shifted in phase by 30° approximately 15 per cent of turns should be added to obtain the desired phase voltage in the winding.

The tolerances for the parameters listed in Tables 2.1 and 2.2 as well as for the rated ratio of transformation are established by the main standard specifications of the power transformers. The main tolerances are given below in Table 2.3.

Table 2.3

Parameters measured	Tolerances, %	Application
Transformation ratio	± 0.5 ± 1	For all transformers unless otherwise specified For transformers with phase transformation ratio of 3 and less
Open-circuit losses	± 15	For all transformers
Short-circuit losses	± 10	Same
Total losses	± 10	Same
Impedance voltage	± 10	Same
No-load current	± 30	Same

The indicated tolerances hold true for the manufactured transformers.

In the process of transformer designing closer tolerances ought to be taken to allow for deviations occurring in production. It is customary to take the tolerances at half their specified values.

2.3. Types and Groups of Winding Connection

Two typical connection groups (phasor groups) have been adopted by the national standard specifications for the power transformers. These are groups 0 and 11.

The *connection group* refers to the phase displacement of the phasors of the line EMFs of the MV and LV windings with respect to the corresponding phasors of the HV winding. This phase displacement is indicated by a figure which, when multiplied by 30° (conventional angular unit) yields the lag in degrees. In the star and delta connections, these lags are multiples of 30° and, therefore, an angle of 30° is taken, for brevity, as an angular unit. Thus, Figure 11 indicates the lag of $11 \cdot 30 = 330^\circ$ and the figure 0 denotes zero shift.

The phase EMFs induced in the HV, MV, LV windings wound on the common magnetic core leg, will be either in phase or out of phase by 180° (i.e., shifted in phase through 6 angular units) depending on the direction of winding the coil (refer to para. 12.3) and on the winding terminal marking.

There are a number of methods used for the determination of the mutual phase shifts of the EMFs in the windings, or, otherwise speaking, the connection groups of a transformer. We shall suggest one of them for consideration.

To make the reasoning simple, we shall take a single-phase transformer with two windings arranged on the core in the manner diagrammatically shown in Fig. 2.1a. Suppose that the currents indicated in the figure by the arrows simultaneously flow through both the windings from the input terminals *A* and *a*. Let these currents flow in the same direction in both the windings, say, counterclockwise, if viewed from the top. In such a transformer, the phase EMFs induced in the HV and LV windings, when the magnetic flux is set up in the core, will be phase-coincident. In this case we obtain the connection group 1/1-0.

Should we change the direction of the coil wind or change the connection of the leads in one of the windings, as is shown in Fig. 2.1b and c, then the phase EMFs will be shifted by 180° (6 angular units), that is, they will be mutually

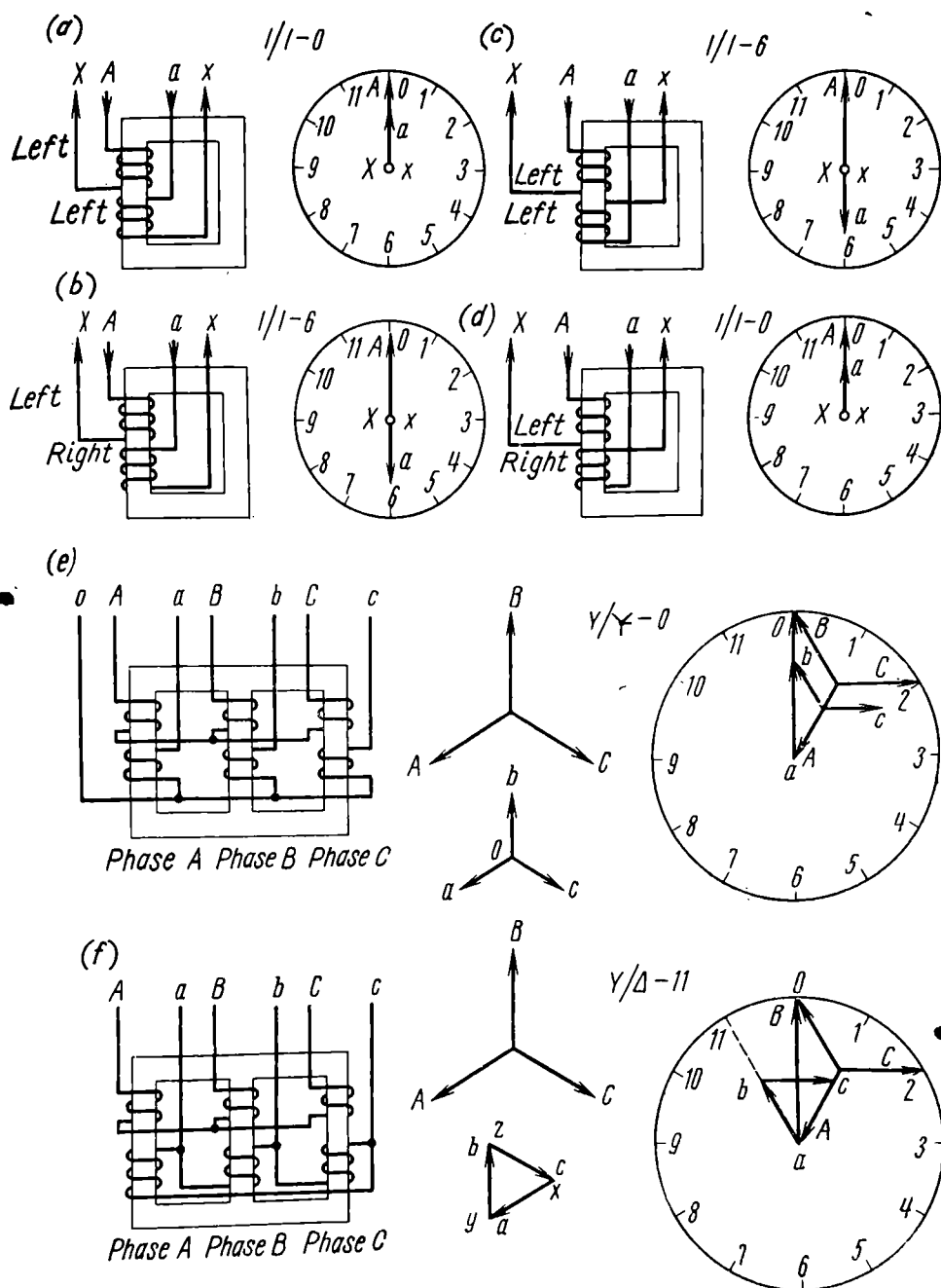


Fig. 2.1. Numerical designation of phasor groups of single-phase and three-phase transformers on the basis of types of winding connection and the direction of wind

(a) single-phase transformer, winding direction for both coils is left-handed, direction of EMFs of HV and LV windings coincide, phasor group 0; (b) same but direction of winding of coils is different (left-handed and right-handed), EMFs are opposing, phasor group 6; (c) same but direction of winding is identical and LV winding leads are interchanged, therefore, EMFs are opposing, phasor group 6; (d) same but direction of winding is different and LV winding leads are interchanged, directions of EMFs coincide, phasor group 0; (e) three-phase transformer, winding direction is identical, star-star connection with a neutral, phasor group 0; (f) same, direction of winding is identical, star-delta, phasor group 11

displaced by half the period. In these cases we obtain the connection group 1/1-6.

Should we now simultaneously change the direction of the wind and change the connection of the terminals in one of the windings, then the phase EMFs will coincide and connection 1/1-0 will be obtained (Fig. 2.1*d*).

The three-phase transformers are usually connected in star or delta. The line EMFs of the HV and LV windings will be phase-shifted through different angles depending on the particular connection used for each winding.

When determining the phase shift, the EMF phasor of the HV winding should be set to 0 in the circle similar to a clock dial. Then, the LV winding EMF phasor, set in accordance with the type of connection, will indicate the phase shift, in angular units or the group of connection.

Figure 2.1 shows the winding connections with the terminal markings, direction of currents through the windings and phasor diagrams enclosed in a circle (clock dial).

✓ In the case of a three-phase transformer, first the *A* and *a* ends of the phasor diagrams for the HV and LV windings are aligned. Then, as was stated above, phasor *AB* of the line EMF of the HV winding is placed in the circle so that the phasor end *B* points to 0. Accordingly, the EMF phasor *ab* of the LV winding will point with its end *b* to the dial figure indicating the connection group. ✓

• The groups of the three-phase transformer connections are shown in Fig. 2.1 *e* and *f*, where types and groups of connections (star-star with the neutral and phasor group 0 and star-delta with phasor group 11) are illustrated.

In the transformers with the standard connection groups 0 and 11, the phase EMFs should be phase-coincident and it will be so if the turns in both the windings are wound in the same direction (if viewing these turns from the line terminals onwards). For this purpose, it is necessary that the direction of winding (be it right-handed or left-handed) and the terminal markings (showing the correct polarities of connecting the leads to the terminals) be interrelated in a definite manner. •

For clarity we shall call all the winding ends the *leads*. Then, of the two leads or ends one will be referred to as the *start* and the other as the *finish* of the winding,

It is customary to regard the winding leads connected to terminals A, B, C (HV winding) and a, b, c (LV winding) as the start of the windings. It should be pointed out, however, that the leads identified by the user as the start and finish of the winding may be identified quite the other way round during manufacture. It is often the case that due to design considerations the lead of the first turn has to be called and marked the finish whilst the last turn produced will be the start of the winding.

2.4. Choice of Basic Core Sizes

It is common to start designing the transformer with the determination of basic core dimensions which define the so-called transformer prototype. These are the core-circle diameter D , i.e., the circle described around the core-leg cross section, the height H of the transformer window and the spacing L between the limb centres (Fig. 2.2).

As is known, the core represents a closed magnetic circuit through which passes the main magnetic flux linked with both the HV and LV windings. The size of the magnetic core and the configuration of the leg depend on the chosen dimensions, configuration and construction of the windings.

The windings of the power transformers are usually made round (wound on the circular cylinder formers) and, therefore, the core leg has a symmetrical stepped cross section inscribed in a circle of diameter D .

As was stated in paragraph 1.4, the transformer dimensions, diameter D among them, depend mainly upon its power. However, besides the power, the transformer dimensions depend on many other factors, like the energy losses, impedance voltage, voltage rating, quality of electrical steel, etc. Hence, it will be fairly complicated to derive a universal and exact formula for determining diameter D for all the probable cases and combinations of given parameters.

In view of the above, it is customary to design transformers by resorting to various approximation methods based on the accumulated experience realized in different formulae, equations, tables, charts, etc. The basic core sizes thus obtained are then verified by a number of computation techniques and, if required, corrections are introduced.

The seemingly complicated accomplishment of this method is not so cumbersome in practice, since the work described above is required only when a new series of power transformers is to be designed. After this series is produced, that

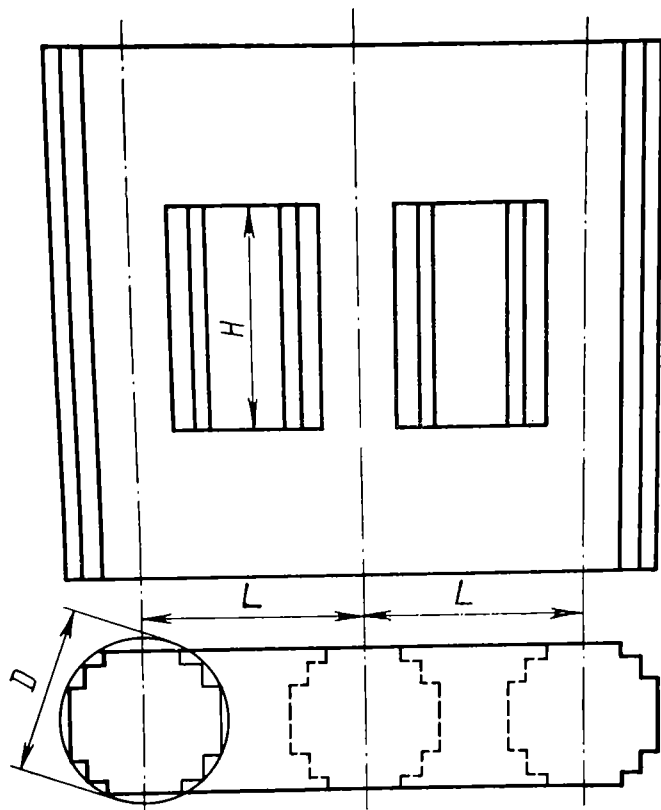


Fig. 2.2. Three-phase magnetic core. Basic dimensions

is, when the assortment of magnetic cores is available to suit the appropriate power ratings, the chosen main sizes of the magnetic core for each type will be invariable. In this case, designing of a transformer of a certain power is reduced to the computation of winding data to meet specified voltage combinations.

2.5. Proportionality Theory and Determination of Basic Core Dimensions

A combination of different transformer design methods proposed by many authors is generally known as the proportionality theory.

The basic sizes of the magnetic core obtained by one of these methods will be further corrected depending on the

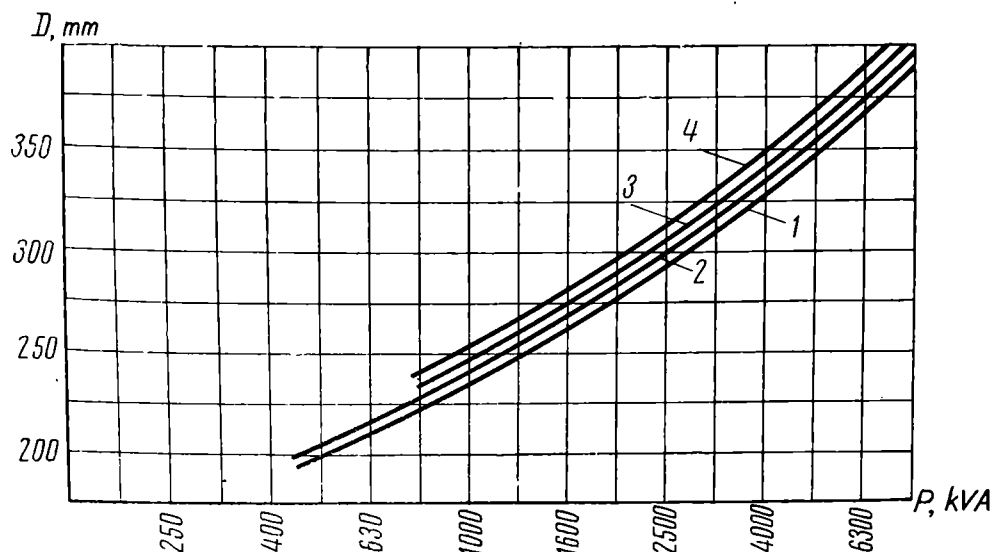


Fig. 2.3. Curves for determining the core diameter of three-phase transformers depending on power and voltage

design considerations, arrangement of the windings in the core window, and desired service parameters (characteristics).

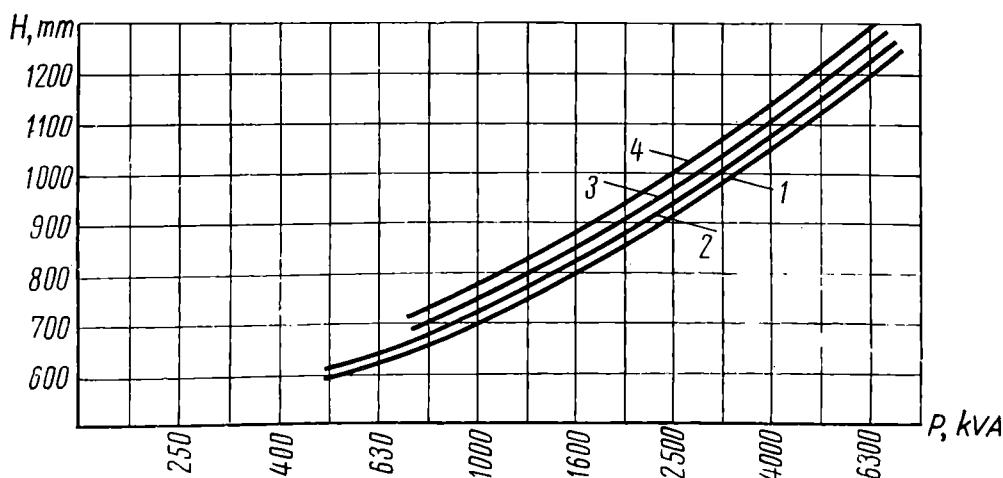


Fig. 2.4. Curves for initial choice of core window height depending on power and voltage

Using the data in Tables 2.1 and 2.2, diameter D may be preliminarily chosen from the curves (Fig. 2.3) as follows: between curves 1 and 2 for voltages of 6 to 10 kV; between

curves 2 and 3 for voltages of 20 kV and between curves 3 and 4 for voltages of 35 kV.

The height H of the transformer window comprises a total height (length) H_{wd} of windings and insulation and gaps between the yokes placed at the ends of the windings. A preliminary choice of this height may be made between curves 1 and 2 for voltages of 6 to 10 kV; between curves 2 and 3 for 20 kV, and between curves 3 and 4 for 35 kV (Fig. 2.4).

After preliminary computation, the transformer window height (H) may be increased or reduced depending on the computation results obtained, i.e., arrangement of the winding turns, leakage inductance, etc.

The data on the choice of insulation gaps are given in Chapter Thirteen.

Review Questions

1. Which of the transformer parameters should be specified for the transformer computation?
2. Which dimensions should be determined at the initial stage of the transformer design computation?

Chapter Three

Magnetic Circuit Computations

3.1. Calculation of the Diameter, Cross Section, Number of Steps of the Core Leg and Yoke, and the Space Factor

The initial choice of diameter D , as has been stated in the foregoing chapter, is made graphically with the aid of the curves illustrated in Fig. 2.3.

The effective cross section A_{leg} , that is, the cross section of the ferromagnetic steel core depends upon the chosen form of the cross section, number of steps and the space factor.

The number of steps must be possibly large because the more the number of steps, the greater the space factor, i.e., the ratio of the effective area to the total area of the leg. However, it is customary practice to limit the number of steps in order to avoid complications in the production process arising from a great variety of laminations. Therefore, the number of steps is chosen with respect to the selected diameter D according to data given in Fig. 14.1, or as indicated below.

Leg diameter, D , mm	up to 80	80-100	90-120	100-200	205-300
Number of steps	3	4	5	6	7

The chosen number of steps determines the number of lamination stacks which constitute the leg section.

The maximum step-shaped cross section can be attained only at certain ratios of the stack width to diameter D . These ratios vary with the different number of steps (see Fig. 14.1).

The width of each stack is derived by multiplying diameter D by an appropriate lamination width factor given in Fig. 14.1.

In practice, however, designers have to depart from the theoretical values of the stack width (and, accordingly, of the lamination width) because of the following reasons:

1. Necessity of using laminations of such sizes as to reduce the waste of steel to a minimum when cutting out laminations from standard-sized steel sheets (widths of laminations are given on page 232).

2. For the leg diameters in excess of 250 mm, when clamping together leg laminations by clamping pins, a space should be provided for compression nuts and washers within the confines of the circumference (see Fig. 14.2).

Besides, when determining the size of stacks it is often necessary to take into account the corrugation of laminations, location of cooling ducts and clamping wedges, etc. Insomuch as this refers only to larger diameters (more than 350 or 400 mm), the above-stated factors influencing the size of stacks will not be considered here.

The cross section of the yoke should theoretically follow the leg section, at least from the view-point of geometry, since the value of the magnetic flux in the yoke is equal to that in the leg. However, the yoke carries no windings and, therefore, its shape, in this respect, is not governed by specific requirements. Therefore, the magnetic core design can be simplified to a certain extent by reducing the number of yoke steps as compared with that of the leg. The transformers of low capacity (size I) have generally a rectangular section yoke. The transformers of size II are usually provided with a two-stepped T-shaped yoke, which facilitates the bringing-out of internal-winding ends, especially when the latter have large cross sections. The larger transformers of size III and above have multi-stepped yokes wherein the number of steps is close or equal to the number of steps in the leg.

The cross-sectional area of a rectangular or two-stepped yoke has to be increased, i.e., reinforced due to the following considerations. In view of the fact that the cross sections of the yoke stacks are not equal to the cross sections of the corresponding stacks in the core leg, the magnetic flux densities in the stacks will be different although the total cross-sectional areas of the yoke and the leg are equal. For instance, in a rectangular yoke the cross section of the middle

stack will be less than that of the middle (larger) stack in a leg and, consequently, the flux density in the middle stack of the yoke will be greater than the mean magnetic flux density. Besides, the flux density will tend to equalize over the entire cross section, which means that a portion of the magnetic flux will leak from one stack into another, causing additional eddy current losses in the steel laminations. This phenomenon occurs mainly in the core corners.

To reduce the eddy current losses and decrease to some extent the redistribution of the magnetic flux among the stacks, the yoke must be reinforced. This reinforcement consists usually in a 10 to 15 per cent increase of the cross section of a rectangular yoke and about a 5 per cent increase for a two-stepped yoke. As a result, the magnetic flux density only in the middle (larger) yoke stack will be approximately 10 per cent higher than the mean magnetic flux density in the core leg.

The yoke reinforcement is especially needed when using cold-rolled steel in which the eddy current losses are appreciably greater than in hot-rolled steel.

The effective area of the leg and the yoke is less than the stepped cross-sectional area by a few per cent because there are insulation layers and air gaps between the core leg and the yoke assembled from thin insulated electrical-steel laminations.

The effective area is the product of the stepped section by the factor of filling this section with steel (space factor).

The space factors are given in Table 11.1 for the case of an ordinary two-sided coating of laminations with a film of varnish.

The basic dimensions H and L of the magnetic core are determined after the computation of windings, which involves the arrangement of turns in the window and therefore the evaluation of the core window dimensions.

3.2. Determination of Core Weight

To determine the weight of the core steel, the basic dimensions of the core should be known. These are the core cross-sectional area A_{core} and yoke area A_y , height H of the window and spacing L between the limb centres.

The H and L sizes are determined depending on the arrangement of windings in the core window.

The height H of the window is equal to the height H_{wdg} of the winding plus the insulation gaps between the yokes and the winding ends (Fig. 3.1); D_{HV} is the outer diameter of the HV winding.

Spacings l_{wdg} between the winding ends and corresponding yokes are selected from Tables 13.1 and 13.4. If the clamping

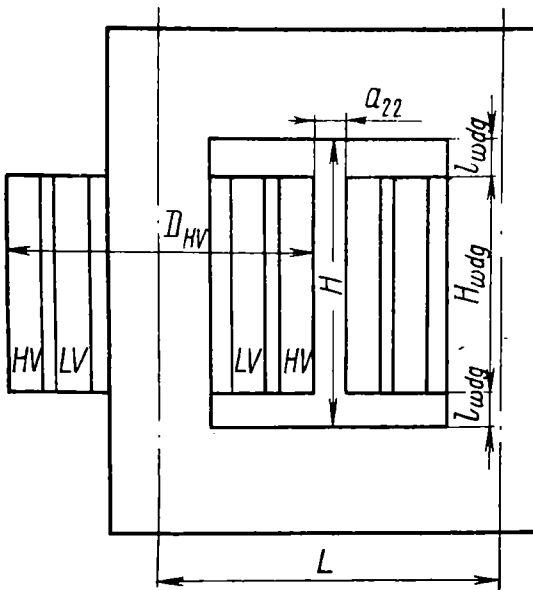


Fig. 3.1. Insulation spacings between winding ends and yokes and between windings of adjacent phases

rings are to be installed in the transformers of 1000 kVA and above, the spacing between the upper winding end and the upper yoke is increased by 65 mm. Occasionally, when, for instance, it is required to bring out the ends of the LV winding of a large cross section, this spacing is still more increased.

The spacing L between the limb centres, as is evident from Fig. 3.1, is equal to the outer diameter of the HV winding plus the insulation gap a_{22} between the HV windings on the adjacent legs. This spacing is found from Table 13.4.

Weight of steel in the legs is

$$G_{st} = N \gamma_{st} A_{leg} H \times 10^3 \text{ kg}$$

where N = number of legs (3 in the case of a three-phase transformer)

γ_{st} = specific weight of electrical steel (7.55 kg/dm³ for hot-rolled steel and 7.65 kg/dm³ for cold-rolled steel)

A_{leg} = effective area of the leg, cm²
 H = leg height, cm

The given equation holds true for a rectangular or stepped yoke with the steps made on the outside of the core.

Due to a more complex geometry of yokes, their weight G_y is determined as the sum of the weight of their main parts G'_y and the weight G''_y of the parts situated at the corners of the core.

Weight of the main parts (in the case of a three-phase transformer) is

$$G'_y = 4\gamma_{st}A_yL \times 10^{-3} \text{ kg} \quad (3.2)$$

Weight of the corner parts of the yokes (in the case of rectangular yokes) is

$$G''_y = 2\gamma_{st}A_{leg}h_y \times 10^{-3} \text{ kg} \quad (3.3)$$

where h_y is the height of the yoke (width of laminations), cm.

If the yokes are of stepped configuration, then the weight of the core corners should be determined separately for each stack, first measuring the volumes of each stack.

For example, in commonly employed two-stepped yokes with 5 or 6 steps the thickness of the larger stack will be

$$b_{y1} = b_1 + 2b_2$$

Then weight of the corners is

$$G''_y = 2\gamma_{st} \times 10^{-3} [A_{leg}H_{y2} + A'_{leg}(H_{y1} - H_{y2})] \text{ kg} \quad (3.3)$$

where H_{y1} and H_{y2} are the heights of the larger and smaller stacks of the yoke, cm²;

A'_{leg} is the effective section of two middle (largest) stacks of the leg, cm².

Otherwise, if the yokes have more complex configurations, the weight is determined by measuring the volumes of parts of individual stacks of the yokes and legs with subsequent summation of the results obtained.

3.3. Calculation of Windings, Currents, Number of Turns and Selection of Wire Gauge

The winding data are calculated on the basis of the phase values of currents and voltages.

The power of a three-phase AC transformer is

$$P = V_{line} I_{line} \sqrt{3} \times 10^{-3} \text{ kVA}$$

where V_{line} is the line voltage, V; I_{line} is the line current, A; Hence,

$$I_{line} = \frac{P \times 10^3}{V_{line} \sqrt{3}} \text{ A}$$

The phase current for star connection is

$$I_{ph} = I_{line}$$

and in the case of delta connection,

$$I_{ph} = \frac{I_{line}}{\sqrt{3}}$$

The assignment for designing the transformer specifies line voltages V_{1line} and V_{2line} , though the windings surrounding each leg should be calculated for phase voltages. Therefore, when calculating the number of turns of the three-phase transformer windings, allowance should be made for the relationships between the phase and line voltages depending on a given winding connection, i.e., $V_{line} = \sqrt{3} V_{ph}$ in star connection and $V_{line} = V_{ph}$ in delta connection.

The number of turns, N , is found from the basic voltage formula of a transformer

$$V_{ph} = 4.44 f N B_{leg} A_{leg} \times 10^{-4} \text{ V}$$

As $f = 50 \text{ Hz}$, then

$$N = \frac{V_{ph} \times 10^4}{222 B_{leg} A_{leg}}$$

where V_{ph} = phase voltage, V

B_{leg} = magnetic flux density in the leg, T

A_{leg} = effective core leg cross section, cm^2

The magnetic flux density depends upon the electrical steel used. For the cold-rolled steel of grades 3320 and 3330 the magnetic flux density is taken to be about 1.7 T.

It will be convenient to determine first the number of turns in the low-voltage winding, (N_{LV}), which has a smaller number of turns:

$$N_{LV} = \frac{V_{ph LV} \times 10^4}{222 \times 1.7 A_{leg}}$$

The number of turns of the LV winding calculated by this formula should be rounded off to the nearest integer.

The number of turns of the HV winding on the core leg should be determined on the nominal step on the basis of the voltage ratio, rather than from the basic voltage formula, otherwise the rounding-off of the number of LV winding turns would not be taken into account. Thus

$$N_{HV} = N_{LV} \frac{V_{ph HV}}{V_{ph LV}}$$

Now, proceeding from a given percentage regulation of the HV winding voltage we can find the number of regulating turns. For instance, with the percentage regulation within ± 5 per cent, the number of regulating turns is

$$N_{reg HV} = \pm 0.05 N_{HV}$$

After that, the number of the HV and LV winding turns can be finally written:

$$\begin{array}{ccc} (N_{HV} + N_{reg HV}) & - N_{HV} & - (N_{HV} - N_{reg HV}) \\ + 5\% & \text{NOMINAL} & - 5\% \end{array} / N_{LV}$$

The size (cross section) of the winding conductors is chosen on the basis of the permissible current density δ in the conductors.

The permissible current density is determined by the chosen type of the winding, conditions of its cooling and amount of load losses (copper losses). In the event of a cylindrical layer winding the current density can be initially assumed to be $\delta = 4 - 4.5$ A/mm² and 3.8 to 4.2 A/mm² for the continuous and helical windings.

The oil-filled transformers utilize rectangular copper and aluminium conductors.

Table 3.1

Double insulation thickness, mm		Cross section of rectangular conductors in mm ² ; size <i>a</i> , mm														
		Size <i>b</i> , mm		1.4	1.6	1.8	2.0	2.24	2.5	2.8	3.15	3.55	4.0	4.5	5.0	5.6
0.54	4.0	4.78	5.38	6.18	6.84	7.64	8.6	9.45	10.65							
	4.5	5.41	6.08	6.98	7.74	8.64	9.72	10.7	12.05	13.6						
0.55	5.0	6.03	6.78	7.78	8.64	9.64	10.8	11.95	13.45	15.2	17.2					
	5.6	6.78	7.62	8.74	9.72	10.8	12.2	13.45	15.1	17.1	19.3	21.5				
0.57	6.3	7.66	8.6	9.86	11.0	12.2	13.75	15.2	17.1	19.3	21.8	24.3	27.5			
	7.1	8.66	9.72	11.15	12.4	13.8	15.5	17.2	19.3	21.8	24.7	27.5	31.1	34.6		
0.59	8.0	9.78	11.0	12.6	14.0	15.6	17.55	19.45	21.8	24.6	27.8	31.1	35.1	39.2	43.9	
	9.0	11.0	12.4	14.2	15.8	17.6	19.8	21.9	24.6	27.8	31.4	35.1	39.6	44.1	49.5	
	10.0	12.3	13.8	15.8	17.8	19.6	22.0	24.4	27.4	30.9	34.9	39.1	44.1	49.1	55.1	
	11.2		15.5	17.7	19.8	22.0	24.7	27.4	30.8	34.7	39.2	43.9	49.5	55.1	61.8	
	12.5			19.8	22.1	24.6	27.6	30.7	34.4	38.8	43.8	49.1	55.4	61.1	69.1	
14.0					27.6	31.0	34.4	38.6	43.5	49.1	55.1	62.1	69.1	77.5		

Note. a and b are the conductor cross section sizes, mm.

The wire gauges, i.e., the combination of sizes of sides a and b in the section of a bare conductor, are standardized. The assortment of conductors given below in Table 3.1 is curtailed as compared with that tabulated in the standard specifications in order to reduce the total number of conductor sizes and to facilitate thereby the supply of the winding material to the Manufacturer.

3.4. Selection of HV and LV Windings and Insulation Gaps. Distribution of Turns in Core Window. Determination of Axial and Radial Winding Structure

Cylindrical double-layer windings may serve as the HV windings for the service voltage rated at up to 690 V and currents up to 2000 A. In the case of larger currents, it is expedient to use helical, simplex or duplex windings.

Continuous windings serve as the LV windings at voltages exceeding 3000 V and also as the HV windings.

Distribution of winding turns under factory conditions requires certain skill and experience. Therefore, when making calculation assignments, the students have, as a rule, to try a few tentative calculation variants of winding distribution until the most suitable one is found.

First, it is necessary to know (or determine), at least approximately, the axial size H_{wdg} (height or length) of the winding.

The axial height of a winding may be approximately found either by using factor β equal to the ratio of the average width of the turn to the winding height, or graphically through the use of the curves shown in Fig. 2.4.

The methods of turn distribution differ with different types of windings.

The cylindrical double-layer LV winding is calculated in the following fashion.

Initially, the turn width is found according to the preselected cross section of the conductor. If the requisite section of the conductor (proceeding from the current density values) exceeds the value given in Table 3.1, two or more parallel conductors are used.

Then, the winding height will be

$$H_{wdg} = nb_{i.c.} \left(\frac{N}{2} + 1 \right) 1.03 \text{ mm}$$

where n = number of parallel conductors

$b_{i.c.}$ = width of the insulated conductor

2 = number of layers

1 = additional space in the layer for one turn,
which account for helical wind of turns

1.03 = factor accounting for non-uniform arrangement of turns

The winding conductor should be chosen of such a width as to obtain the winding height close to the preset value.

The obtained winding height H_{wdg} is then rounded off to the nearest higher integer which is a multiple of 5.

The radial size of a double-layer winding is

$$a_1 = (a_{i.c.} + 1) 2 + a_{c.d.} \text{ mm}$$

where $a_{i.c.}$ = radial size (thickness) of insulated conductor

1 = number which accounts for the thickness of cotton-tape covering wound on each layer

2 = number of layers

$a_{c.d.}$ = radial size of the oil cooling duct, usually taken to be 5 to 6 mm

The helical, simplex winding is calculated in the following manner.

Initially, a certain axial size is found which is required for the arrangement of a conductor and oil cooling duct,

$$b_{i.c.} + b_{c.d.} = \frac{1.02H_{wdg}}{N+4}$$

where $b_{i.c.}$ = width of the insulated conductor

$b_{c.d.}$ = oil cooling duct width (usually 5 to 6 mm)

4 = 1 + 3 = number accounting for the additional space for one turn wound along the helix and the space for three groups of transposed conductors

Then, the sizes and the number of parallel branches of conductors are chosen from the winding wire table in the column pertaining to the predetermined value of $b_{i.c.}$.

The height of the helical, simplex winding, (H_{wdg}), will be equal to the sum of axial sizes (heights) of the insulated conductor $b_{i.c.} (N + 4)$ and oil-cooling duct $b_{c.d.} (N + 3)$. In view of the fact that the oil-cooling ducts are formed by means of the pressboard spacers which are compressed during the finishing of the winding by 4 to 6 per cent of their original thickness, the height of the winding will be

$$H_{wdg} = b_{i.c.} (N + 4) + b_{c.d.} (N + 3) (0.94 \text{ to } 0.96)$$

The obtained size is then rounded off to the next higher integer.

The radial size of a helical winding is

$$a_1 = 1.03 na_{i.c.} \text{ mm}$$

where 1.03 = factor accounting for the non-uniform arrangement of winding turns

n = number of parallel conductors

$a_{i.c.}$ = radial size of an insulated conductor

The helical duplex winding is calculated in the similar fashion.

Since the transposed conductors in this winding do not need any additional space, the winding height comes to

$$H_{wdg} = b_{ins} 2 (N + 1) + b_{c.d.} (2N + 1) (0.94 \text{ to } 0.96)$$

This equation implies that the ducts are provided between all branches (paths) of transposed conductors.

As regards the calculation of a continuous (disc) HV winding, it should be pointed out that certain limitations are imposed on the choice of the total number of coils because the HV winding is provided with the voltage-changing taps which should be brought out from the transitions between the coils due to considerations of design and manufacture.

In the case of the usual voltage regulation (± 5 or $\pm 2 \times 2.5$ per cent), the total number of HV winding turns constitutes $1.05 N_{HV}$ (where N_{HV} is the number of turns on the nominal step). Therefore, the total number of the HV winding turns should be a multiple of 20 or 22 and, moreover, it should be an even number so that both the start and finish of the winding could be brought to the top. Under these conditions, the voltage-changing coils will have nearly the same number of turns as the main coils.

When choosing the requisite number of coils, a trial and error method is applied. That is why the desired number is not always selected at once. To this end, the following calculation technique is offered.

Supposing the required cross section of the conductor has been so chosen according to a current value, on the assumption that the current density is about 4 A/mm^2 , that the ratio of the sides b and a of the conductor cross section is $b/a = 2$ to 5 . The width of the oil-cooling duct is assumed to vary from 5 to 8 mm . Now we approximately calculate the total number of coils which can be arranged in height H_{wdg} and which must be a multiple of 20 to 22 . After such preliminary calculations, we can safely select quite definite sizes of the winding conductor and cooling duct and also the number of turns. After a few trials of this kind, a certain skill is acquired and the final selection of the desired values becomes easy enough.

If the calculated conductor cross section is too large as to a given current magnitude (if the cross section is taken from the right-hand side of the wire data Table 3.1), then it will be expedient to select two or even three parallel wires which will facilitate somewhat the winding operation.

Distribution of the turns on the coils is regarded to be correct if the number of turns on the coils differ by not more than one. It is customary to wind a coil with an integral number of turns, although fractional numbers are also possible. In the latter case it is better to have the fractional part greater than half the turn.

The technique of distributing the turns in the continuous winding can be best illustrated by the following example.

Problem 3.1. The HV winding current is 78 A , the axial size H_{wdg} of the winding is 795 mm , the total number of turns for each voltage step constitutes $416-396-376$ turns.

Choose the winding conductor data and determine the number of coils and the number of turns in coils.

This problem has two solutions.

Solution I

With the current density given at 4 A/mm^2 , we can find the required cross section of the conductor,

$$s_c = \frac{78}{4} = 19.5 \text{ mm}^2$$

Assuming the number of coils to be equal to 42, we shall obtain the following height of one coil with an axial duct:

$$\frac{795}{42} = 18.9 \text{ mm}$$

That is, with a duct of 7.5 mm, the conductor width must be
 $18.9 - 7.5 = 11.4 \text{ mm}$

The tabulated data give a wire with dimensions of 11.2 by 1.8 mm and a cross section of 19.8 mm². Then, the current density is corrected as follows:

$$\delta = \frac{78}{19.8} = 3.94 \text{ A/mm}^2$$

Distribution of the turns among the coils is done in a manner described below.

Out of the total number of the coils (42), 4 coils (10 per cent) will be voltage changing and the remaining 38 will be the main coils. The thirty-eight main coils carry 376 turns. If we take 10 turns per each coil, we obtain $10 \times 38 = 380$ turns, i.e., 4 turns too many. Therefore, we have to take 9 turns per 4 coils out of 38.

Thus,

34 main coils, each 10 turns	= 340
4 main coils, each 9 turns	= 36
4 voltage-changing coils, each 10 turns	= 40
Total,	416 turns

Each regulating step comprises $2 \times 10 = 20$ turns.

Now we proceed with the calculation of an axial structure of the HV winding.

The paper-insulated wire (11.2×1.8) has a rated size (with insulation) of 11.79×2.39 mm (plus 0.59 mm on either side). Thus,

42 coils of 11.79 mm each	= 495 mm
40 ducts of 7.5 mm each	= 300 mm
1 enlarged duct of 15	= 15 mm

H_{wdg}	= 810 mm
Compression of spacers	= 15 mm

Total, 795 mm

Compression of the spacers in the ducts comes to $\frac{15}{300+15} \times 100\% = 4.7\%$, which is within the specified limits.

The enlarged duct is made in the centre of the winding where it has a break in accordance with the voltage tapping circuit. On the HV winding voltage step (—5 per cent) the intercoil voltage at the point of break is about 10.5 per cent $\left(\frac{40}{376} \cdot 100\% \right)$ of the phase voltage.

Solution II

Let the number of coils be 64. Then, the width of one coil with a duct will be

$$\frac{795}{64} = 12.4 \text{ mm}$$

Taking the duct width at 5 mm, select a conductor size of 7.1×2.8 mm, with a section of 19.3 mm^2 .

Current density is

$$\delta = \frac{78}{19.3} = 4.04 \text{ A/mm}^2$$

Out of 64 coils, 6 will be the voltage changing coils and the remaining 58, the main coils.

Reasoning as in Solution I above, we shall obtain the following turn distribution:

28 main coils of 7 turns each	= 196
30 main coils of 6 turns each	= 180
4 voltage changing coils of 7 turns each	= 28
2 voltage changing coils of 6 turns each	= 12

Total, 416 turns

Each voltage regulating step contains $2 \times 7 + 1 \times 6 = 20$ turns.
Calculation of the axial structure:

64 coils, each 7.67 mm	= 491 mm
62 ducts, each 5 mm	= 310 mm
1 enlarged duct of 10 mm	= 10 mm

	811 mm
Compression of spacers	= -16 mm

$$H_{wdg} = 795 \text{ mm}$$

Compression is

$$\frac{16}{320} \times 100 = 5\%$$

The spacers forming oil-cooling ducts are stamped from the electrical pressboard 1.5, 2, and 2.5 mm in thicknesses. Therefore, the sizes of the ducts should be multiple of the above numbers, i.e., they may be 4.5, 5, 6, 7.5, 8, 9, 10 mm, etc.

The radial size of the continuous winding is determined in the same manner as for the helical winding, with the only difference that the number of parallel wires, N , is substituted here by number N_c of the coil turns

$$a_2 = 1.03 N_c a_{i.c.} \text{ mm}$$

where N_c is the greatest number of turns in a coil.

Review Questions

1. How are the number and sizes of steps in the section of a core leg and yoke determined?
2. What is the steel core space factor?
3. Write the basic formula of the transformer voltage.
4. What are the uses of the double-layer cylindrical, continuous and helical windings?

Chapter Four

Computation of Open-Circuit Conditions of Transformer

4.1. Open-Circuit Characteristics According to Standards. No-Load Current and Open-Circuit Losses

A *transformer* is said to be *on open-circuit* when its primary winding is fed from an AC source and the secondary winding is open. In the open-circuit condition the transformer is just excited; i.e., voltage is induced in the secondary winding but the transformer does not supply the load.

The open-circuit conditions are employed, in part, for testing the manufactured transformer and determining some of its operating characteristics by the so-called *open-circuit tests*. These characteristics are:

- (a) open-circuit loss, P_0 ;
- (b) no-load current, I_0 ;
- (c) transformation ratio, K .

The open-circuit losses and no-load currents of the power transformers are specified in the appropriate standards. Their values are given in Tables 2.1 and 2.2.

The characteristics of the properly designed and manufactured transformer should not go beyond the permissible limits set forth by the standard specifications. It should be stressed, however, that though minimum permissible values of the open-circuit losses and no-load currents are not specified, they should not be much below the required values, as this would be a clear indication of insufficient use of active components, i.e., ferromagnetic and conducting materials, and, as a consequence, of an excessive cost of the transformer.

In view of the above, it is the aim of the student, and the designer at the manufacturing plant, to design a transformer so as to obtain the above-listed characteristics, to

say nothing of the basic transformer parameters, i.e. kVA rating and service voltage, as close to the standardized values as possible.

4.2. Transformation Ratio

By definition the *transformation ratio* K is the ratio of the primary and secondary EMFs equalling the turns ratio:

$$K = \frac{E_1}{E_2} = \frac{N_1}{N_2}$$

As the resistance drops in the power transformer windings are negligible, it is customary to regard the EMFs and the primary and secondary voltages as equal, that is:

$$E_1 \approx V_1; \text{ and } E_2 \approx V_2$$

and hence,

$$K \approx \frac{V_1}{V_2} \quad (4.1)$$

4.3. Open-Circuit Losses

The open-circuit losses P_0 of a transformer comprise mainly the magnetic core losses. The copper losses in the primary winding caused by the no-load current are negligible and, therefore, are usually ignored.

The losses in the steel parts of the transformer framework and dielectric losses in insulation occurring under the open-circuit conditions are unamendable to calculation and are usually accounted for by the extra loss factor determined experimentally.

The steel losses consist of the hysteresis loss and eddy-current loss. The percentage relationship between these losses differs with the grade of the electrical steel used. In the hot-rolled high-alloy steel the eddy-current loss constitutes about 20 to 30 per cent of the total core loss, and in the case of the cold-rolled higher-alloy steel, 65 to 75 per cent of the total core loss.

When calculating the core loss and also measuring it during the transformer tests, it is customary to determine the total core losses without breaking them into separate components as there is no need for this.

The core losses depend upon the grade of steel, its thickness, current frequency, magnetic flux density and weight. Specific loss values, that is, the loss per unit weight expressed in W/kg, are indicated in the appropriate standards. However, the core losses of the manufactured transformer are influenced by a number of additional factors, such as the kind of insulation of the laminations, use of annealing of the laminations after their treatment, quality of assembly, core construction, etc. It is not always possible to consider all these factors with sufficient accuracy and, therefore, the calculations should be based on the use of the graphs and tables constructed and derived in testing the actual transformer cores. The basic data taken from these tables are corrected by the coefficients which account for the specific features of the magnetic core design and technology of core production.

The values of specific losses and a reactive power of cold-rolled electrical steel 0.35 mm thick may be taken for training purposes from Table 4.1.

Table 4.1

Magnetic induction, B , teslas	Specific losses, P , W/kg	Specific reactive power Q_i		Magnetic induction, B , teslas	Specific losses, W/kg	Specific reactive power Q_i	
		var/kg	var/cm ²			var/kg	var/cm ²
1.50	1.11	4.7	1.98	1.63	1.41	7.4	2.81
1.51	1.13	4.9	2.05	1.64	1.43	7.6	2.87
1.52	1.15	5.1	2.12	1.65	1.46	7.8	2.94
1.53	1.17	5.3	2.18	1.66	1.49	8.0	3.00
1.54	1.19	5.5	2.24	1.67	1.52	8.2	3.06
1.55	1.21	5.8	2.30	1.68	1.54	8.4	3.12
1.56	1.24	6.0	2.37	1.69	1.57	8.6	3.19
1.57	1.26	6.2	2.44	1.70	1.60	8.8	3.26
1.58	1.28	6.4	2.50	1.71	1.63	9.0	3.32
1.59	1.31	6.6	2.56	1.72	1.66	9.2	3.38
1.60	1.33	6.8	2.62	1.73	1.69	9.4	3.44
1.61	1.36	7.0	2.68	1.74	1.72	9.6	3.51
1.62	1.38	7.2	2.74	1.75	1.75	9.8	3.58

Notes. 1. Specific losses of 0.5-mm steel sheets are higher by 25%.

2. Specific reactive power values of 0.5-mm steel sheets nearly equal the tabulated data.

Since the magnetic flux densities in the core legs and yokes differ, the core loss is determined separately for the cores and yokes and the results are then added. Thus, the core loss P_0 is determined by

$$P_0 = P_{leg}G_{leg} + P_yG_y$$

where P_{leg} and P_y are the specific tabulated losses pertaining to certain induction values, W/kg; G_{leg} and G_y are the weights of legs and yokes, kg.

The following correction factors should be introduced into the core loss values obtained from Eq. 4.2:

(a) extra loss factor K_Φ which allows for the non-uniform flux density in the leg and yoke sections. This factor may be taken from Table 4.2

Table 4.2

Yoke section	Extra loss factor K_Φ of core with leg diameter D , mm			
	up to 200	200-300	300-500	over 500
Rectangular	1.0-1.01	1.02-1.05	1.05-1.1	1.1-1.15
Stepped	1.0	1.0-1.02	1.03-1.05	1.05-1.07

(b) the values of specific losses P_{leg} and P_y should be increased by 10 per cent in the case of non-annealed cold-rolled steel;

(c) the losses rise at the corners of the core assembled from the cold-rolled steel laminations of ordinary design (butt-joint) due to the fact that the flux paths and the direction of steel rolling are not parallel. With the magnetic flux density varying from 1.5 to 1.7 teslas in the steel sheets 0.35 mm thick, this loss increment may be allowed for by the factor 1.5, and 1.3, for the steel sheets 0.5 mm thick. The weight of the steel core corners is multiplied by these factors. The calculation of corner parts is given in the example of transformer calculation assignments at the end of the book.

4.4. No-Load Current

No-load current I_0 flows through a primary winding of the open-circuit transformer. For an ideal transformer (loss-free transformer) this is a purely magnetizing current which

produces a magnetomotive force (ampere-turns) required for the creation of the main magnetic flux linked with both windings of the transformer.

In an actual transformer the no-load current consists of a reactive component (magnetizing current) and a resistive component (compensating for the no-load loss).

The no-load current and its components are usually expressed in per cent of the rated current.

The resistive component

$$I_{0R} = \frac{P_o}{P} \cdot 100\%$$

or expressing the rated power in kVA,

$$I_{0R} = \frac{P_o}{10P} \% \quad (4.2)$$

As far as the magnetizing current is concerned, it depends at a definite magnetic induction value, as do the open-circuit losses, mainly on the grade of steel used and on the core design.

The calculation of the reactive power (volt-amperes reactive) consumed by the core steel is similar to the calculation of losses. The values of specific reactive power Q are taken from tables drawn for each steel grade on the basis of experimental data.

In view of the fact that the main magnetic flux must pass through the joints (gaps) between the laminations, an additional reactive power is required to overcome the resistance of the joints, which depends upon the magnetic circuit design (butt-joint or interleaved core construction), size of the air gap, interleaving pattern, and, obviously, induction.

In the USSR transformer-manufacturing industry employs exclusively interleaved cores and the tables giving the values of specific reactive power per joint (gap) in var/cm² have been calculated specifically for such transformers.

Thus, the magnetizing current is

$$I_{0mag} = \frac{Q_{leg}G_{leg} + Q_y G_y + N_j Q_{leg/j} A_{leg} + N_y Q_{y/j} A_y}{10P} \% \quad (4.3)$$

where Q_{leg} and Q_y = specific reactive powers for legs
and yokes in var/kg

G_{leg} and G_y = weight of the legs and yokes

N_{leg} and N_y	= number of joints in the core leg and yoke sections
$Q_{leg/j}$ and $Q_{y/j}$	= specific reactive power per joint in var/cm ²
A_{leg} and A_y	= cross-sectional areas of legs and yokes (the space factor is not accounted for) in cm ² .

The number of joints in a three-phase transformer is $N_{leg} = 3$ and $N_y = 4$ (Fig. 4.1). The large-size transformers

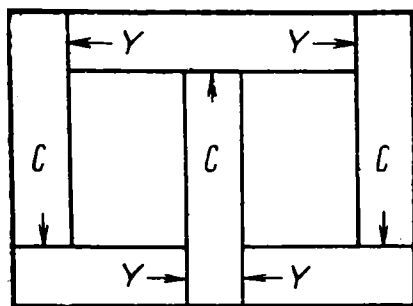


Fig. 4.1. Lamination joints in three-phase core

whose laminations are made composite because of their length, have an increased number of joints.

The values of specific reactive power Q for cold-rolled steel can be taken from Table 4.1.

A factor allowing for the increase in the reactive power at the corners of the steel core should be introduced to the value of the magnetizing current, derived from Eq. 4.7, in the butt-joint core assembled from the cold-rolled steel laminations in the same manner as it is done in calculating the core losses. This reactive power increment is caused by the decrease in the magnetic permeability of cold-rolled steel in those parts of the core where direction of the magnetic flux lines is not coincident with the direction of steel rolling. For a magnetic flux density of 1.5 to 1.7 T, the reactive power increment factor in the core corners will be approximately 3 to 3.5.

The initial magnetization curve (Fig. 4.2a) showing the relationship between the magnetizing current $I_{0\ mag}$ and magnetic induction has a knee point, near which the steel saturation occurs. A rise in the magnetic induction beyond the knee point brings about a sharp increase in the magnetizing current. This is the main reason why the peak induc-

tion value is limited to 1.4 or 1.45 T for hot-rolled steel and 1.6 to 1.7 T for cold-rolled steel. Besides, increased induction much distorts the magnetizing current wave-form which becomes non-sinusoidal (Fig. 4.2b).

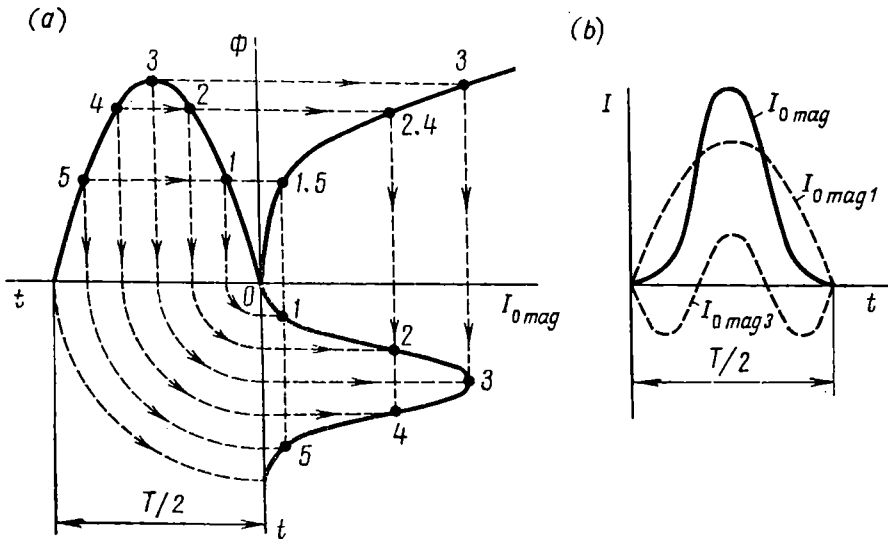


Fig. 4.2. Magnetizing current curve

(a) curve plotted by the given saturation point (3); (b) resolution of non-sinusoidal curve into sinusoidal components of the 1st (I_{0mag1}) and 3rd (I_{0mag3}) harmonics

Eventually, this gives rise to the magnetic fluxes of higher harmonics of which the 3rd-harmonic flux is most troublesome. In the case of a star-star connection (with no neutral) this flux, being in phase in all three legs, will inevitably earth to the transformer steelwork (yoke beams, tank, etc.) producing additional and hardly accountable losses.

4.5. Resistive and Reactive Components of No-Load Current

The no-load current I_0 is determined as the phasor sum of the magnetizing current (reactive component) I_{0mag} and resistive component I_{0R} . Since phasors I_{0mag} and I_{0R} are phase-shifted through a quarter period (by 90°), this current will be

$$I_0 = \sqrt{I_{0mag}^2 + I_{0R}^2}$$

In the case of a three-phase transformer, the obtained no-load current value will be the mean value for all the three phases. The actual magnitude of the no-load current will be smaller in the centre leg than in the extreme legs.

As the resistive component is relatively small, it can be safely assumed that $I_0 \approx I_{0 \text{ mag}}$.

4.6. No-Load Current and Open-Circuit Losses as Functions of Primary Voltage

Fluctuations of the primary voltage applied to the transformer, normally varying within $\pm 5\%$ of the rated value (and occasionally more), cause changes in the induction of transformer total flux within the same range. Theoretically, the open-circuit losses are proportional to the second degree of the induction value. However, in the actual transformers, this relationship is pronounced more markedly over the applied magnetic induction range and the losses are nearly proportional to the third degree of induction, which implies that the open-circuit losses much depend upon the primary voltage applied to the transformer. Variations in the core specific losses are illustrated in Table 4.1.

The dependence of the magnetizing current on the magnetic induction value is even more pronounced. Since for the purpose of economy of ferromagnetic and conducting materials power transformers are designed with possibly higher values of induction approximating the steel saturation region, any further increase in induction with the rise in voltage results in a sharp inrush of the magnetizing current. This is clearly indicated in Table 4.1 which shows the relationship between reactive powers Q , var/kg, and Q_j , var/cm², and induction B .

4.7. Phasor Diagram and EMF Balance Equation of No-Load Transformer

The no-load current I_0 produced in the primary winding of the transformer which accepts power at voltage V_1 is relatively small in contrast with the rated primary current of the transformer.

The magnetomotive force (MMF) produced by the no-load current of the primary winding, $F_0 = I_0 N_1$, excites a variable magnetic flux, the main portion of which with the crest value Φ is closed through the magnetic core. The main magnetic flux threads the turns of the primary and secondary windings and induces there EMFs, E_1 and E_2 .

In addition to the main magnetic flux, there is a leakage flux Φ_{l1} , the flux lines of which are closed through the air and cut only the primary winding turns inducing a leakage EMF, E_{l1} .

The leakage flux is relatively small as compared with the main magnetic flux as the former encounters high reluctance (diamagnetic medium). Therefore, the leakage EMF is also very small as compared with the EMF induced by the main magnetic flux ($E_{l1} \ll E_1$).

The resistance voltage drop V_{R1} in the primary winding with resistance R_1 will be $V_{R1} = I_0 R_1$.

According to Kirchhoff's second law, the phasor sum

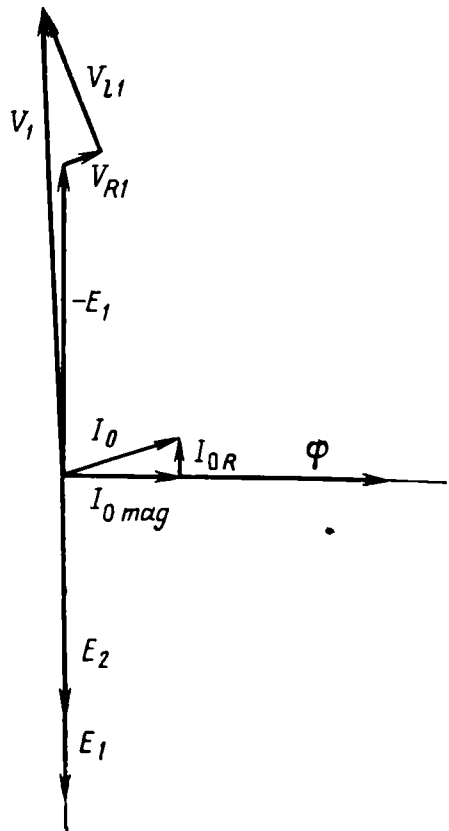


Fig. 4.3. Phasor diagram of an open-circuit transformer

of the EMFs is equal to the sum of the voltage drops in any closed path of a circuit, i.e.,

$$\dot{V}_1 + \dot{E}_1 + \dot{E}_{l1} = \dot{V}_{R1}$$

Since the primary voltage $\dot{V}_1$ applied to the transformer should be balanced by the EMFs and voltage drops in the circuit, the balance equation of the EMFs is usually written

as follows:

$$\dot{V}_1 = -\dot{E}_1 - \dot{E}_{l1} + \dot{V}_{R1}$$

The leakage EMF (E_{l1}) may be regarded as the reactive voltage drop V_{l1} with the opposite sign.

The balance equation may be represented in the form of a no-load phasor diagram shown in Fig. 4.3.

Plotted on the vertical axis of this diagram are the EMF phasors, with the main flux amplitude phasor Φ constructed on the horizontal axis. The E_1 and E_2 positive phasors are directed downwards because these EMSs lag flux Φ by a quarter period.

The same diagram shows the phasors of no-load current $\dot{I}_0$ and its resistive ($\dot{I}_{0R}$) and reactive ($\dot{I}_{0\text{ mag}}$) components. The phasor of the resistance voltage drop (V_{R1}) coincides in direction with phasor $\dot{I}_0$ and the reactive voltage drop phasor $\dot{V}_{\text{mag } 1}$ leads phasor $\dot{I}_0$ by 90° (quarter period).

The phasor $\dot{V}_1$ becomes the sum of phasors $-\dot{E}_1$, $\dot{V}_{\text{mag } 1}$ and $\dot{V}_{R1}$.

Review Questions

1. What are the line and phase transformation ratios and when do they have different values?
2. What is the composition of the open-circuit losses?
3. Why should the open-circuit losses be determined separately for the core legs and yokes?
4. Why does the magnetizing current of power transformers have the non-sinusoidal waveform?
5. Write the EMF balance equation for a no-load transformer.

Chapter Five

Calculation of Transformer Load Conditions

5.1. On-Load Service Parameters. Impedance Voltage and Short-Circuit Losses

Let us briefly discuss the physical processes occurring in a transformer on load.

The current load of a transformer is determined by any kind of impedance, be it active, inductive, capacitive or compound, connected to the terminals of the secondary winding. Due to insertion of impedance, the secondary load current will flow through the closed circuit thus formed

$$I_2 = \frac{V_2}{Z_2}$$

where Z_2 is the circuit impedance.

The secondary current I_2 produces the MMF (ampere-turns) $I_2 N_2$ which must excite a certain magnetic flux Φ_m in the core. According to Lenz's law this flux induces a primary magnetomotive force $I'_1 N_1$ equal to $I_2 N_2$ in the primary winding linked with the flux. By the same law, the magnetomotive force produces a magnetic flux Φ_m which is equal but opposite in direction to the flux Φ_m . The magnetic fluxes become mutually cancelled but the load current appears in the primary winding:

$$I'_1 = I_2 \frac{N_2}{N_1}$$

Thus, when a load is connected to the transformer secondary, load currents appear in both windings, flowing in opposite directions.

In the case of power transformers, the primary and secondary voltages are regarded with sufficient accuracy to be

proportional to the turns ratio, and, therefore:

$$I'_1 = I_2 \frac{N_2}{N_1} = I_2 \frac{V_2}{V_1} \text{ or } V_1 I'_1 = V_2 I_2$$

Hence, the primary and secondary powers are equal, which agrees with the energy conservation law.

The transformer receiving power with voltage V_1 on the primary side, gives up the same power (minus losses) at another voltage V_2 on the secondary side.

The primary winding carries also the no-load current I_0 and, therefore, the total primary current I_1 , with the transformer on load, must be equal to the sum (generally to the phasor sum) of the load current I'_1 and the no-load current I_0 , i.e.,

$$\dot{I}_1 = \dot{I}'_1 + \dot{I}_0$$

However, the no-load current is usually ignored, assuming that $I_1 \approx I'_1$, inasmuch as the no-load current constitutes merely a few per cent of the nominal load current and because the two currents are summed up at some angle to one another.

The load currents I_1 and I_2 passing through the transformer windings produce in them resistance voltage drops $V_{R1} = I_1 r_1$ and $V_{R2} = I_2 r_2$ and inductive voltage drops V_{l1} and V_{l2} .

The resistance voltage drops occur due to copper losses (Joule effect) in the windings equal to $P_{sc1} = I_1^2 r_1$ and $P_{sc2} = I_2^2 r_2$. The sumtotal of losses in the windings, P_{sc1} and P_{sc2} , cover the major portion of the transformer short-circuit losses.

The inductive drops are produced on account of the magnetic leakage fluxes linking each winding separately. The inductive drops compensate for the leakage EMFs that is

$$V_{l1} = -E_{l1} \text{ and } V_{l2} = -E_{l2}$$

In the equivalent transformer the total resistance voltage drop is equal to the sum of the resistance voltage drops in both windings, i.e.,

$$V_R = V_{R1} + V_{R2}$$

Similarly, the total inductive drop is equal to the sum of the inductive drops

$$V_l = V_{l1} + V_{l2}$$

On the phasor diagram of the equivalent transformer the phasor sum of the resistance and inductance voltage drops, the phasors of which are at an angle of 90° to one another, represents the full voltage drop referred to as the *impedance voltage* V_{sc} of a transformer. Hence,

$$V_{sc} = \sqrt{V_R^2 + V_l^2}$$

(This is also illustrated in Fig. 5.4.)

The impedance voltage and short-circuit losses are the important service parameters specified in the appropriate standards. Their values are given above in Tables 2.1 and 2.2.

The impedance voltage and the short-circuit losses determine the transformer efficiency and its regulation, which will be discussed in more detail below.

5.2. Short-Circuit Losses

Short-circuit losses are defined as the power measured with a wattmeter during the short-circuit test (see Sec. 5.6).

As was already mentioned, the major portion of the short-circuit losses is the copper losses in the windings or, to be more exact, in the winding conductors. Besides the short-circuit losses also include the extra (stray) losses in the conductor, tank walls and structural elements of a transformer as well as the losses in the taps.

The copper losses in the windings caused by the load currents through these windings are calculated by the basic formula of electric current expended in the circuit,

$$P = I^2 R$$

Designers often resort to formula (5.2) which includes current density and winding conductor weight G_{wdg}

$$P_{sc} = I^2 R = \delta^2 s_c^2 \frac{l}{s_c} \rho \delta^2 s_c l$$

Since

$$G_{wdg} = \gamma s_c l \times 10^{-3} \text{ and } s_c l = \frac{G_{wdg} \times 10^3}{\gamma}, \text{ we obtain}$$

$$P_{sc} = \frac{\rho}{\gamma} \delta^2 G_{wdg} \times 10^3 = K_{sc} \delta^2 G_{wdg} \text{ (in watts)} \quad (5.2)$$

where s_c = conductor cross section in mm^2

l = conductor length in m

ρ = copper (or aluminium) resistivity in $\frac{\text{ohm} \cdot \text{mm}^2}{\text{m}}$

γ = specific gravity, kg/dm^3

G_{wdg} = weight of the winding conductor, kg

The coefficient K_{sc} is taken from Table 5.1 which follows.

Table 5.1

Conductor material	K_{sc}	
	20°C	75°C
Copper	1.97	2.4
Aluminium	10.5	12.75

The losses are calculated separately for each winding and then summed up because the current densities and the conductor weight differ in the primary and secondary windings.

5.3. Extra (Stray) Losses and Losses in Leads and Taps

The extra losses of the loaded transformer occur both in the windings and in the individual elements of the construction, mainly in the tank. These losses arise from eddy currents induced in the conductors and tank walls by leakage fluxes.

When calculating the extra losses it is assumed that the magnetic lines of force of leakage flux Φ_l run parallel to the main flux path, simultaneously linking both windings as shown in Fig. 5.2.

The winding wires, having a certain radial thickness, are cut by the magnetic leakage flux, which leads to a generation of eddy current losses in the wires. The extra losses are ta-

ken into account by coefficient K_{Φ} by which the main copper losses in the winding conductors are multiplied.

The theoretical computation of coefficient K_{Φ} is a fairly complicated problem and, therefore, it is determined through the use of various semi-empirical formulae.

For the power transformers with rectangular-conductor windings

$$K_{\Phi} = 1 + \frac{m^2 - 0.2}{9} (a')^4 \quad (5.3)$$

where m = number of coil layers

a' = effective radial size of a conductor equal to

$$a' = \frac{a}{1.03} \sqrt{\frac{b}{b_{ins}} \times \frac{f}{50} K_R}$$

a = radial size of a conductor, cm

b = axial size of a bare conductor, cm

b_{ic} = axial size of an insulated conductor, cm

K_R = Rogowski coefficient (see Sec. 5.4).

f = frequency, Hz

In the case of a round conductor of diameter d

$$K_{\Phi} = 1 + \frac{m^2 - 0.2}{15.25} (d')^4 \quad (5.4)$$

where d' is the effective diameter of a conductor equaling

$$d' = \frac{a}{1.03} \sqrt{\frac{d}{d_{ic}} \times \frac{f}{50} K_R}$$

(d_{ic} is the diameter of an insulated conductor, cm).

With the conductor diameter of up to 3.5 mm (large diameter conductors are rarely used and are commonly replaced by rectangular conductors) the percentage of the extra losses is relatively small and, therefore, usually ignored in the case of round conductors.

When calculating the losses, due consideration should be given to the fact that in the conductor layer adjoining the main leakage path the losses are three times the mean value determined by the above-given equations, which can lead to overheating of this layer.

Besides, if the conductor size is large, local overheating may occur due to the bending of the leakage flux at the point

of exit from the winding. This should be also taken into account when calculating the losses in large transformers.

The above-stated equations show that the amount of extra losses depends very much (to the fourth power) on the conductor radial size. It is therefore considered good practice to avoid using thick and bulky conductors or, if it is necessary to obtain a greater total cross-sectional area of the winding conductor, use should be made of a few parallel groups of transposed conductors (see below Sec. 12.7, helical windings).

In addition to the extra losses in the winding conductors, the leakage fluxes are also productive of extra losses in the tank walls, yoke clamping bars and other bulky elements of the transformer construction. These losses result both from the eddy currents and remagnetization.

Theoretical computation of these losses is also hard to be made as the exact direction of the magnetic leakage flux and its configuration are usually unknown.

For the power transformers of size I, extra losses P_t in the tank walls are usually disregarded, as they are relatively small. In the case of transformers of larger capacity, several empirical formulae are applied for computation. The simplest formula for the calculation of extra losses in the transformers of size II and III is

$$P_t = 0.007 P^{1.5} \text{ W} \quad (5.5)$$

The losses in the leads between the windings and bushing insulators constitute a part of the short-circuit losses and should be considered when the latter losses are calculated.

The losses in the leads may be accurately determined after designing the transformer, that is, after the length and the cross-sectional area of the leads are known. It is better however to know the amount of these losses, at least approximately, beforehand, to avoid the introduction of corrections into the winding data after the design development is completed.

The losses in the leads of power transformers of identical kVA ratings manufactured on an industrial scale do not differ materially. Therefore the preliminary value of the losses P_{lead} in the leads of a three-phase transformer may be deter-

mined with a good approximation by the empirical formula

$$P_{lead} = 0.051 I \sqrt[4]{P} \text{ W} \quad (5.6)$$

where I is the line current through the winding, A.

The above formula clearly shows that the value P_{lead} at currents not higher than 100 to 200 A is relatively small and therefore, in practice, it will be sufficient to determine the losses in the leads of power transformers, sizes II and III, only for the LV windings.

5.4. Leakage Fluxes in a Loaded Transformer

When a transformer is on load, the load currents set up in its windings produce corresponding magnetomotive forces $I_1 N_1$ and $I_2 N_2$. As a consequence, leakage fluxes are formed

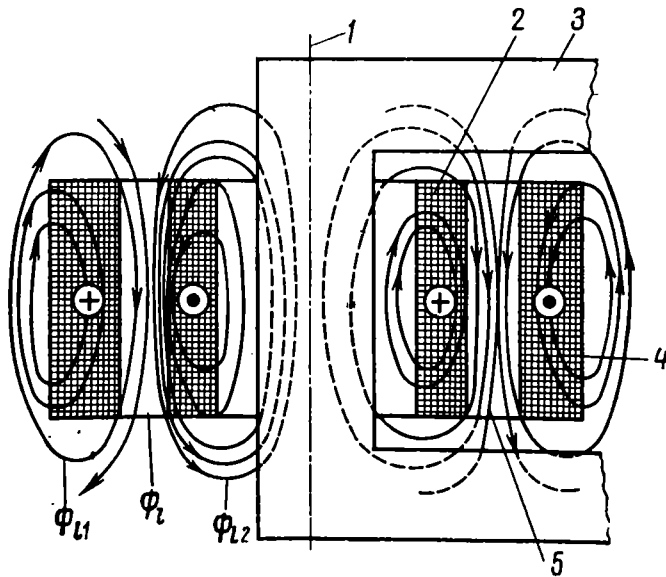


Fig. 5.1. Leakage fluxes in a loaded transformer

1—common axis of transformer core and windings; 2—secondary winding; 3—core; 4—primary winding; 5—leakage path between windings

around each winding as shown in Fig. 5.1. Since the currents through the primary and secondary windings are opposite-directed, as stated by Lenz's law, both leakage fluxes produced by the MMFs of both the windings are added to form the resultant mutual leakage flux Φ_l passing through the gap between the windings and called the *main leakage path*.

Due to the presence of the leakage fluxes in both the windings, there must be a certain reactance voltage drop indicated as V_{l1} and V_{l2} (see Fig. 5.4). On the phasor diagram of the impedance voltage triangle, the phasors V_{l1} and V_{l2} of the reactance voltage drops are 90° ahead of phasors V_{R1}

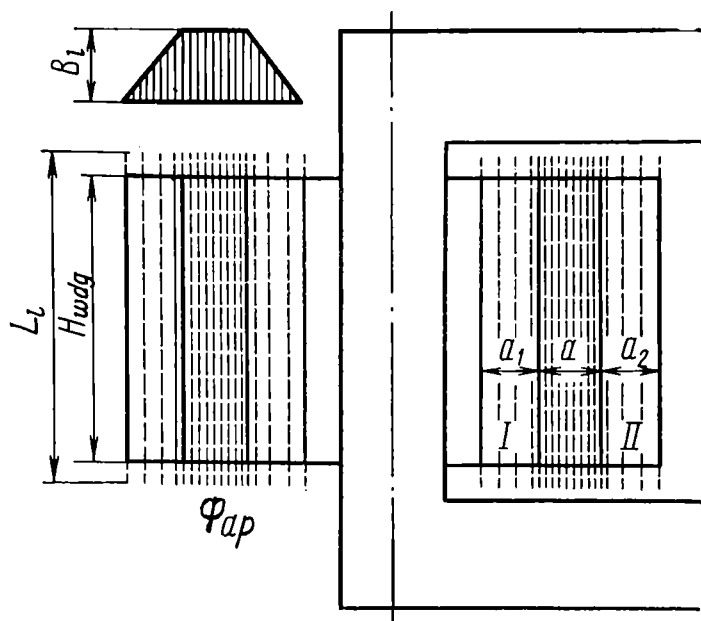


Fig. 5.2. Simplified apparent leakage flux equivalent of actual leakage flux

and V_{R2} of the resistance voltage drops coincident with the direction of the load-current phasors.

To calculate the reactance voltage drop, it is necessary to know the reluctance offered to the leakage flux of a given transformer.

As the calculation of the actual leakage flux is extremely complicated because of its complex form, it is substituted by the calculation of a more simple apparent leakage flux Φ_{ap} equivalent to the actual one. Direction of magnetic lines of force of the apparent flux is assumed to be rectilinear.

The form of the apparent flux is assumed to be the simplest, cylindrical one, with the direction of the flux lines in parallel with the axis of the windings. The length of the apparent flux (according to professor W. Rogowski's research) is found to be only a little longer than the height of the win-

dings, as the main resistance (reluctance) to the leakage flux is confined to its most dense portion, namely, the main path. Outside the windings the leakage flux has a relatively low density and passes partially through the transformer steelwork, thus encountering low reluctance.

Figure 5.2 illustrates an apparent leakage flux for the case of the concentric arrangement of windings of the cylindrical form and equal height.

The difference between winding height H_{wdg} and length L_l of the apparent leakage flux is accounted for by the coefficient K_R introduced by W. Rogowski.

$$H_{wdg} = K_R L_l$$

$$\text{where} \quad K_R = 1 - \frac{a + a_1 + a_2}{\pi H_{wdg}} \quad (5.7)$$

a = radial size of the main path, cm

a_1, a_2 , = radial sizes of the windings, cm

H_{wdg} = axial size of the winding, cm

5.5. Determination of Reactance Voltage Drop

The reactance voltage drop is found from the basic voltage formula

$$V_l = 4.44fN\Phi_l \text{ (V)}$$

where Φ_l is the total leakage flux passing along the windings and linked with one turn of the winding.

Leakage flux density B_l at any point of the magnetic field is proportional to the MMF (ampere-turns) enclosing this point or, in the case of a transformer, a cylindrical surface drawn through a leakage flux line.

Figure 5.3 shows a sectional view of both windings and a diagram of magnetic flux distribution illustrating the development of a reactance drop formula.

As has been already stated, the primary and secondary magnetizing forces are equal and opposite-directed:

$$I_1 N_1 + I_2 N_2 = 0$$

At the edges of the windings area (points 0_1 and 0_2) the flux density is zero because there are no ampere-turns permeated by the flux lines distributed over the winding

outer surface. The flux density across the width of the coils tends to crowd from the periphery of the coil towards the main flux path because the flux is set up by those ampere-turns which envelope a certain magnetic line or with which it is interlinked.

The maximum leakage flux density is in the main path and remains uniformly distributed throughout its width.

As an aid in reasoning it is usual to assume that the ampere-turns are evenly distributed throughout the winding section. Then, the distribution of ampere-turns and, consequently, the flux density B_l in the radial direction of the winding area may be represented by a trapezium diagram known as Kapp's trapezium shown in Fig. 5.2 and 5.3.

The product of $N\Phi_l = NB_lA$ is called the *flux linkage*. As

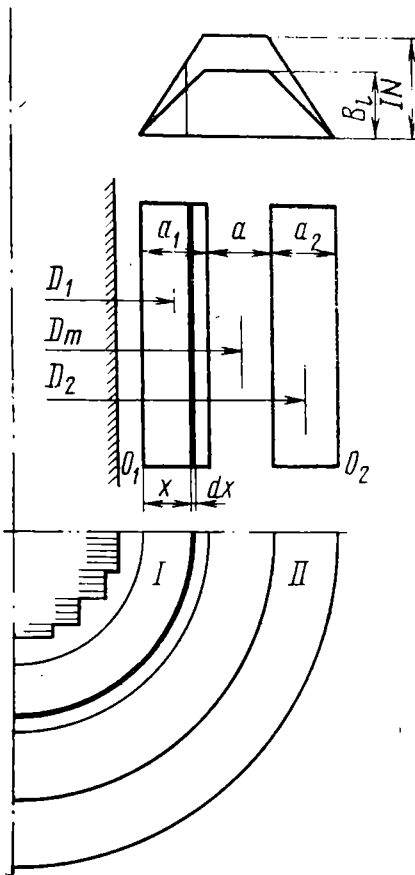


Fig. 5.3. Diagram elucidating the derivation of reactance voltage drop formula

the N and B_l are variable quantities, the total flux linkage is determined as a sum of elementary linkages

$$N\Phi_l = \sum N_x B_x dA_x$$

To make the solution easier, for each of the three winding portions with radial sizes a_1 , a and a_2 the flux linkage values are found separately.

At the mid portion a of the main path the ampere-turns and the flux are constant since the values of N and B_l do not change here and therefore the flux linkage in this portion will be

$$(N\Phi_l)_a = NB_l A_a = N_l B_l \pi D_m a$$

where $A_a = \pi D_m a$ = cross-sectional area of portion a , m^2
 D_m = medium diameter of the main leakage flux path, m .

Any magnetic line in the portion a will be linked with all the turns of either primary I or secondary II .

Calculation of the flux linkage in the portion a_1 is made by way of integration of the elementary flux linkages.

Let us select an elementary area in winding I in the form of a field tube (flux-permeated cylinder) with the wall spaced at a length x from point O_1 situated at the extreme edge of winding I . This point will be regarded as an origin of coordinates.

The magnetic flux permeating this cylinder is

$$d\Phi_x = B_x dA_x = B_l \frac{x}{a_1} \pi (D_1 - a_1 + 2x) dx$$

where D_1 is the medium diameter of winding I , m .

This magnetic flux is linked with the turns $N_x = N_1 \frac{x}{a_1}$ arranged left of the dx area (see Fig. 5.3).

Consequently, the total flux linkage in the a_1 portion is

$$(N\Phi_l)_{a_1} = \int_0^{a_1} N_1 \frac{x}{a_1} B_l \frac{x}{a_1} \pi (D_1 - a_1 + 2x) dx$$

To facilitate integration, the obtained integral is broken into two integrals. The first will include terms $D_1 - a_1$ (out of the terms enclosed in brackets) and the second, $2x$.

Placing the constant values outside the integral gives

$$(1) \frac{N_1 B_l \pi (D_1 - a_1)}{a_1^2} \int_0^{a_1} x^2 dx = \frac{N_1 B_l \pi (D_1 - a_1)}{a_1^2} \cdot \frac{a_1^3}{3} =$$

$$= N_1 B_l \pi (D_1 - a_1) \frac{a_1}{3}$$

$$(2) \frac{2N_1 B_l \pi}{a_1^2} \int_0^{a_1} x^3 dx = \frac{2N_1 B_l \pi}{a_1^2} \cdot \frac{a_1^4}{4} = N_1 B_l \pi \frac{a_1^2}{2}$$

Hence, the flux linkage in the portion a_1 will be equal to the sum of the obtained results

$$\begin{aligned}(N\Phi)_{a_1} &= N_1 B_l \pi \left[(D_1 - a_1) \frac{a_1}{3} + \frac{a_1^2}{2} \right] = \\ &= N_1 B_l \pi \left(D_1 \frac{a_1}{3} + \frac{a_1^2}{6} \right) = N_1 B_l \pi \left(D_1 + \frac{a_1}{2} \right) \frac{a_1}{3}\end{aligned}$$

Similarly determined is the total flux linkage in the portion a_2 (no derivation is given)

$$(N\Phi)_{a_2} = N_2 \frac{E_1}{E_2} B_l \pi \left(D_2 - \frac{a_2}{2} \right) \frac{a_2}{3} = N_1 B_l \pi \left(D_2 - \frac{a_2}{2} \right) \frac{a_2}{3}$$

where D_2 is the mean diameter of winding II , m.

The number of turns N_2 of winding II is reduced to the number of turns N_1 of winding I by using a conventional reduction formula

$$N'_2 = N_2 \frac{E_1}{E_2} = N_1$$

Thus, the total flux linkage of the entire winding zone will be equal to the sum of flux linkages in the three portions

$$\begin{aligned}N\Phi_l &= (N\Phi_l)_a + (N\Phi_l)_{a_1} + (N\Phi)_{a_2} = \\ &= N_1 B_l \pi \left[D_{av} a + \left(D_1 + \frac{a_1}{2} \right) \frac{a_1}{3} + \left(D_2 - \frac{a_2}{2} \right) \frac{a_2}{3} \right]\end{aligned}$$

In the power transformers whose line voltage does not exceed 35 kV, the radial sizes of the HV and LV windings are nearly alike, therefore, we can assume with sufficient accuracy that $a_1 \approx a_2$. This will greatly simplify the obtained expression for flux linkage.

Removing the brackets and substituting D_1 and D_2 by $D_m - a - a_1$ and $D_m + a + a_2$ give

$$\begin{aligned}N\Phi_l &= N_1 B_l \pi \left[D_m a + \left(D_m - a - \frac{a_1}{2} \right) \frac{a_1}{3} + \right. \\ &+ \left. \left(D_m + a + \frac{a_2}{2} \right) \frac{a_2}{3} \right] = N_1 B_l \pi \left[D_m \left(a + \frac{a_1 + a_2}{3} \right) + \right. \\ &\quad \left. + \frac{a_2}{3} (a_2 - a_1) + \frac{a_2^2 - a_1^2}{6} \right]\end{aligned}$$

It is easily seen that at $a_1 \approx a_2$, i.e., $a_2 - a_1 \approx 0$, the two last terms are negligibly small and may be ignored,

due to which the expression in the square brackets becomes appreciably simplified

$$N\Phi_l = N_1 B_l D_m \left(a + \frac{a_1 + a_2}{3} \right) = N_1 B_l \pi D_m \Delta$$

where $\Delta = a + \frac{a_1 + a_2}{3}$ is called the *reduced leakage path*.

It should be pointed out that the expression enclosed above in the square brackets has to be calculated exactly (without the above-indicated simplification) whenever sizes a_1 and a_2 materially differ, as they do, for example, in the high-voltage transformers.

In the case of the air (non-magnetic) medium, the following equation showing the relationship between the flux density, the MMF (ampere-turns) and the length of the flux path will be true:

$$B_l = \frac{0.4\pi \sqrt{2} I N}{L_l} 10^{-2}$$

On substituting this expression, the flux-linkage equation will take the following form:

$$\begin{aligned} N\Phi_l &= N_1 \frac{0.4\pi \sqrt{2} I_1 N_1 \times 10^{-2}}{L_l} \pi D_m \Delta 10^{-4} = \\ &= \frac{0.4\pi^2 \sqrt{2} I_1 N_1^2 D_m \Delta \times 10^{-6}}{L_l} \end{aligned}$$

This can be substituted into the transformer voltage formula

$$V_l = 4.44 f N \Phi_l = \frac{4.44 f 0.4\pi^2 \sqrt{2} I_1 N_1^2 D_m \Delta \times 10^{-6}}{L_l} \text{ V}$$

Substituting $L_l = \frac{H_{wdg}}{K_R}$ and $4.44 = \pi/\sqrt{2}$ and expressing the reactance voltage drop in per cent of the rated voltage (multiplying it by 100) we obtain:

$$\begin{aligned} V_l &= \frac{100}{V_1} = \frac{0.8\pi^3 f I_1 N_1^2 D_m \Delta K_R \times 10^{-6}}{H_{wdg}} = \\ &= \frac{2480 f I_1 N_1^2 D_m \Delta K_R \times 10^{-6}}{V_1 H_{wdg}} \% \end{aligned}$$

and, ultimately, after the last substitution $f = 50$ Hz and $\frac{V_1}{N_1} = e_N$ in V/turn, we obtain a practical formula use

ful for the calculation of the reactance voltage drop

$$V_l = \frac{IND_m \Delta K_l}{806e_N H_{wdg}} \% \quad (5.8)$$

where D_m , Δ and H_{wdg} are in cm.

In calculating the transformer parameters, it is often found necessary to determine the given reactance drop value.

The study of the derived formula shows that whenever the precalculated value V_l is to be changed, it is best first to change the size a , viz., the width of the main leakage path. If, however, it cannot be done (because of insulation problems or because, for instance, the size a has to be appreciably increased), it will be necessary either to change the winding height H_{wdg} or to alter the number of turns N , although it involves complete recalculation of the transformer design data.

5.6. Impedance Voltage

The transformer impedance voltage which represents a full voltage drop in the transformer is measured by means of short-circuit tests. The test consists in short-circuiting the secondary (usually LV) winding and energizing the primary through a voltage regulator. The short-circuit test diagram is given in Fig. 15.5.

The voltage is stepped up from zero until the ammeter reads the rated current I_1 . As the secondary winding is a closed loop, the rated current I_2 ($I_1 N_1 = I_2 N_2$) also starts flowing in it.

Due to the absence of the external secondary circuit, the power indicated by the wattmeter is called the *short-circuit losses* P_{sc} which comprise, as was already mentioned in Sec. 5.2, the copper losses in the windings, extra (stray) losses and the small copper losses in the leads.

The voltage applied to one of the windings to set up a current in the excited winding corresponding to a rated power with the other winding short-circuited, is called the *impedance voltage*. This voltage V_{sc} compensates for the resistance and reactance voltage drops in both the windings caused by currents I_1 and I_2 and is therefore the full voltage drop of the transformer.

The impedance voltage is a few per cent of the rated voltage (from 5.5 to 7.5% for the transformers of sizes *I*, *II*, *III* with a service voltage of 35 kV). The magnetic saturation, and, accordingly, the no-load loss and the open-circuit current are fairly low and can be neglected during the impedance voltage calculation.

The phasor diagram of the transformer short-circuit may be derived from the simplified phasor diagram for the equivalent transformer whose secondary voltage phasor V'_2 is taken as zero. The ABO right triangle with its legs equalling

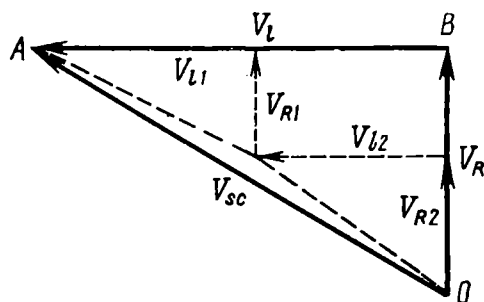


Fig. 5.4. Impedance voltage triangle (phasor diagram)

the sum of resistance and reactance drops in both the windings is referred to as an impedance triangle (Fig. 5.4).

The impedance voltage V_{sc} and its components V_R and V_l are best expressed in per cent of the rated voltage.

Calculation of the leakage-flux voltage V_l was discussed above in Sec. 5.5.

The resistance component V_R depends upon the amount of the short-circuit losses and its equation is derived in the following manner.

According to Ohm's law (for each winding)

$$V_{R1} = I_1 R_1 \quad \text{and} \quad V_{R2} = I_2 R_2$$

or if the voltage drop is expressed in per cent of the rated voltage

$$V_{R1} = \frac{V_{R1}}{V_1} \cdot 100 = \frac{I_1 R_1}{V_1} \cdot 100 = \frac{I_1^2 R_1}{V_1 I_1} \cdot 100 = \frac{P_{sc1}}{P} \cdot 100\%$$

$$V_{R2} = \frac{V_{R2}}{V_2} \cdot 100 = \frac{I_2 R_2}{V_2} \cdot 100 = \frac{I_2^2 R_2}{V_2 I_2} \cdot 100 = \frac{P_{sc2}}{P} \cdot 100\%$$

$$V_R = V_{R1} + V_{R2} = \frac{P_{sc1} + P_{sc2}}{P} \cdot 100 = \frac{P_{sc}}{P} \cdot 100\%$$

The short-circuit loss is usually expressed in W, and rated power, in kVA. Therefore, we finally obtain

$$V_R = \frac{P_{sc}}{1000P} \cdot 100\% = \frac{P_{sc}}{10P} \% \quad (5.9)$$

Since the hypotenuse in the above impedance voltage triangle represents the impedance voltage (V_{sc}), this voltage can be expressed through its components as

$$V_{sc} = \sqrt{V_R^2 + V_L^2}$$

The relationships between V_R and V_L vary and depend on the transformer capacity. In the transformers of very low capacity (with the rated power of up to 1kVA), the reactive component is low and the impedance voltage V_{sc} may be regarded as equal to V_R . With a rise in power, the value of the reactive component increases somewhat and in the largest transformers the impedance voltage becomes nearly equal to the reactive component V_L .

Review Questions

1. What is the transformer load?
2. Why does the load current also start flowing through the primary winding when the secondary winding is on load?
3. Why are the losses in the loaded transformer called short-circuit losses?
4. Where and why do the extra losses appear?
5. What is the reactance drop and how does it occur?
6. What are the reduced leakage path and Rogowski's coefficient?
7. What is the impedance voltage?
8. What is the impedance voltage triangle?

Chapter Six

Voltage Regulation and Efficiency

6.1. Computation of Voltage Regulation

Voltage regulation, ΔV , of a transformer is by definition the difference between the rated secondary voltage $V_{2 \text{ rated}}$ and the secondary voltage V_2 obtained or set up across the terminals of the secondary winding under load conditions and at a specified power factor $\cos \phi_2$.

The *rated secondary voltage* of a power transformer is the secondary voltage determined by a transformation ratio K without regard to voltage drops caused by no-load current. Practically, this voltage is the secondary open-circuit voltage

$$V_{2 \text{ rated}} = V_1 \frac{N_2}{N_1} = \frac{V_1}{K}$$

The change in the secondary voltage is expressed in per cent of the rated secondary voltage

$$\Delta V = \frac{V_{2 \text{ rated}} - V_2}{V_{2 \text{ rated}}} \cdot 100\% \quad (6.1)$$

The change in the voltage magnitude occurs due to resistance and reactance drops across the primary and secondary windings of the transformer.

The computation of voltage regulation is based on a phasor diagram of the equivalent transformer (Fig. 6.1) referred to the lagging load. When constructing this diagram, it is assumed that the secondary winding is equivalent to the primary and that the no-load current is zero.

The impedance voltage triangle ABC should be reconstructed so that one of the legs of the newly-constructed triangle could be the continuation of the phasor V'_2 . For

for this purpose, a semi-circumference is described, with the hypotenuse AC taken as a diameter, and a triangle ACD is constructed as shown in Fig. 6.2.

Let chords CD and AD be expressed in per cent of the

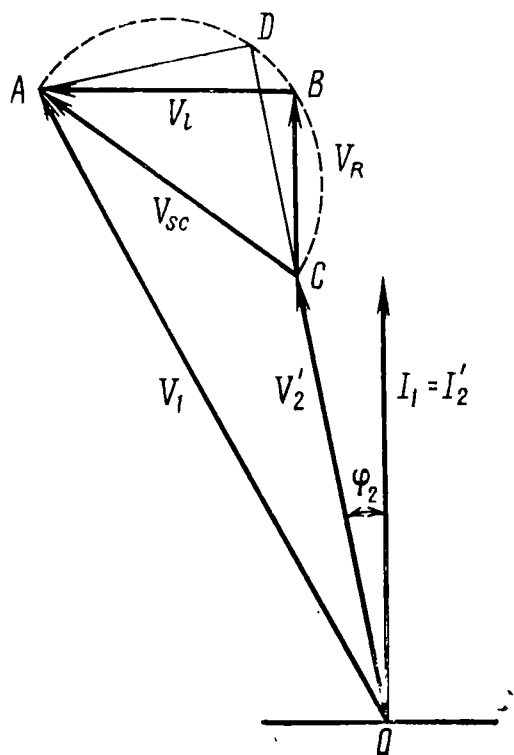


Fig. 6.1. Equivalent transformer phasor diagram explaining the derivation of a voltage regulation formula

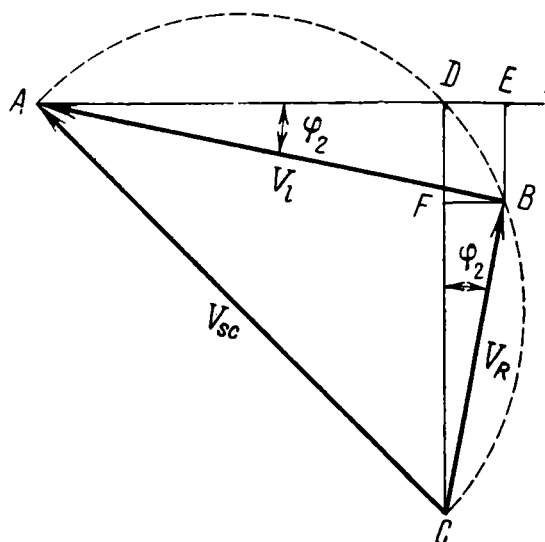


Fig. 6.2. Impedance voltage triangle reconstructed for the derivation of a voltage regulation formula

primary voltage phasor V_1 and the obtained values be respectively designated through m and n . Then

$$m = \frac{CD}{V_1} \cdot 100\%; \quad n = \frac{AD}{V_1} \cdot 100\%$$

For the right-angled triangle ADO (Fig. 6.1)

$$AO^2 = OD^2 + AD^2 = (OC + CD)^2 + AD^2$$

or expressing the chords through respective phasors, we obtain:

$$V_1^2 = \left(V_2' + \frac{m}{100} \cdot V_1 \right)^2 + \left(\frac{n}{100} V_1 \right)^2$$

Whence,

$$V'_2 = \sqrt{V_1^2 - \left(\frac{n}{100} V_1\right)^2} - \frac{m}{100} V_1$$

Let us transform to a certain extent the voltage regulation equation, knowing that $V_1 = KV_2 \text{ rated}$ and $V'_2 = KV_2$ (according to equivalence conditions):

$$\begin{aligned} \Delta V &= \frac{V_2 \text{ rated} - V_2}{V_2 \text{ rated}} \cdot 100 = \frac{KV_2 \text{ rated} - KV_2}{KV_2 \text{ rated}} \cdot 100 = \\ &= \frac{V_1 - V'_2}{V_1} \cdot 100 = \left(1 - \frac{V'_2}{V_1}\right) 100\% \end{aligned}$$

Substituting the equation of V'_2 in the formula gives

$$\begin{aligned} \Delta V &= \left[1 - \frac{\sqrt{V_1^2 - \left(\frac{n}{100} V_1\right)^2} - \frac{m}{100} V_1}{V_1}\right] 100 = \\ &= \left[1 - \sqrt{1 - \left(\frac{n}{100}\right)^2} + \frac{m}{100}\right] \cdot 100\% \end{aligned}$$

For the formula to be simplified, the expression

$$\sqrt{1 - \left(\frac{n}{100}\right)^2} \text{ may be expanded by Newton's}$$

binomial theorem

$$\begin{aligned} \sqrt{1 - \left(\frac{n}{100}\right)^2} &= \left[1 - \left(\frac{n}{100}\right)^2\right]^{1/2} = 1^{1/2} - \frac{1}{2} \left(\frac{n}{100}\right)^2 + \\ &+ \frac{1}{2} \cdot \frac{1}{4} \left(\frac{n}{100}\right)^4 - \dots \end{aligned}$$

The terms of this series beginning with the third are fairly small and can be neglected. Taking the two first terms gives

$$\Delta V = \left[1 - 1 + \frac{1}{2} \left(\frac{n}{100}\right)^2 + \frac{m}{100}\right] 100 = m + \frac{n^2}{200} \%$$

Let us determine the values of m and n by expressing them through resistance and reactance drops (V_R and V_I).

Now let us refer to Fig. 6.2 and study triangles ABC and ADC . Draw lines $BE \parallel CD$ (as far as the continuation of cathetus AD) and $BF \parallel AD$. From the triangles BFC and

BAE it can be easily seen that

$$CD = CF + FD = CF + BE = BC \cos \varphi_2 + AB \sin \varphi_2$$

and

$$AD = AE - DE = AE - BF = AB \cos \varphi_2 - BC \sin \varphi_2$$

The catheti BC and AB of the impedance voltage triangle referred to a phasor V_1 of the primary voltage represent the resistive and reactive components of this triangle, i.e.,

$$V_R = \frac{BC}{V_1} \cdot 100\% \text{ and } V_l = \frac{AB}{V_1} \cdot 100\%$$

Thus, with the expression (6.2) taken into account, we obtain the final form of the voltage regulation equation:

$$\begin{aligned} \Delta V = m + \frac{n^2}{200} = V_R \cos \varphi_2 + V_l \sin \varphi_2 + \\ + \frac{(V_l \cos \varphi_2 - V_R \sin \varphi_2)^2}{200} \end{aligned} \quad (6.3)$$

The angle φ_2 of phase shift of the load current I_2 relative to voltage V_1 under the lagging and leading loads has the opposite signs. Accordingly, the terms comprising $\sin \varphi_2$ should also have the opposite signs.

Therefore, the formula of voltage regulation can be written in the general form

$$\Delta V = V_R \cos \varphi_2 \pm V_l \sin \varphi_2 + \frac{(V_l \cos \varphi_2 \mp V_R \sin \varphi_2)^2}{200} \quad (6.4)$$

where the upper signs (plus and minus) preceding $\sin \varphi_2$ refer to a lagging load, and the lower signs, to a leading load.

Let us consider some specific cases when the voltage regulation equation becomes more simplified.

At a resistive load, when $\cos \varphi_2 = 1$ and, consequently, $\sin \varphi_2 = 0$,

$$\Delta V = V_R + \frac{V_l^2}{200} \quad (6.4)$$

At $V_l < 5\%$, when the last term in the equation (6.4) may be neglected,

$$\Delta V = V_R \cos \varphi_2 \pm V_l \sin \varphi_2 \quad (6.5)$$

and at a resistive load (special case) $\Delta V = V_2$.

Problem 6.1. Calculate the transformer regulation at $\cos \phi_2 = 0.8$ if $V_R = 2.4\%$ and $V_I = 5\%$ (lagging load).

Solution

$$\Delta V = 2.4 \times 0.8 + 5 \sqrt{1 - 0.8^2} + \frac{(5 \times 0.8 - 2.4 \times 0.6)^2}{200} = 1.92 + 3 + 0.03 = 4.95\%$$

Problem 6.2. Calculate ΔV , at a leading load if $\cos \phi_2 = 0.7$, $V_R = 4\%$ and $V_I = 4.5\%$.

Solution

$$\Delta V = 4 \times 480.7 - 4.5 \sqrt{1 - 0.7^2} = 2.8 - 3.2 = -0.4\%$$

The negative value of the voltage regulation obtained in the solution to Problem 6.2 indicates that the secondary voltage can increase somewhat at a leading load and at a sufficiently large angle ϕ_2 .

With a change in the load it can be taken that the change in the voltage magnitude will be proportional to the load current I_2 . To prove this, it is sufficient to establish that the resistance and reactance drops included in the equation also vary in proportion with the load current.

In the reactance drop equation

$$V_I = \frac{I_2 N_2 D_m \Delta K_R}{806 e_N H_{wdg}}$$

with a change in the load, all the values, except for the I_2 , are constant and therefore, $V_I \propto I_2$.

The resistance drop is equal to the sum of the resistance drops across the primary and secondary windings

$$V_R = V_{R1} + V_{R2} = \frac{I_1 R_1}{V_1} \cdot 100 + \frac{I_2 R_2}{V_2} \cdot 100$$

Substituting I_1 by $I_2 \frac{N_2}{N_1}$ and neglecting the changes in resistances R_1 and R_2 caused by the variations in the winding temperature and also neglecting the inappreciable change in the magnitude of voltage V_2 , we can write

$$V_R = \frac{I_2 \frac{N_2}{N_1} R_1}{V_1} \cdot 100 + \frac{I_2 R_2}{V_2} \cdot 100 = I_2 \left(\frac{\frac{N_2}{N_1} R_1}{V_1} + \frac{R_2}{V_2} \right) 100 \propto I_2$$

Thus, the resistance drop is also proportional to the load current.

If we neglect the third term in Eq. 6.4 because of its relatively small value, that is, if we apply equation 6.5, we can easily see that since the values V_R and V_L are proportional to the load current I_2 , the change in voltage regulation ΔV will be also proportional to it and hence,

$$\Delta V \equiv I_2 \quad (6.6)$$

6.2. Transformer Output Voltage Regulation Characteristic

The output voltage regulation characteristic is the relationship between the secondary current and voltage at changing load, constant primary voltage V_1 and at the specified power factor $\cos \phi_2$ for the secondary circuit.

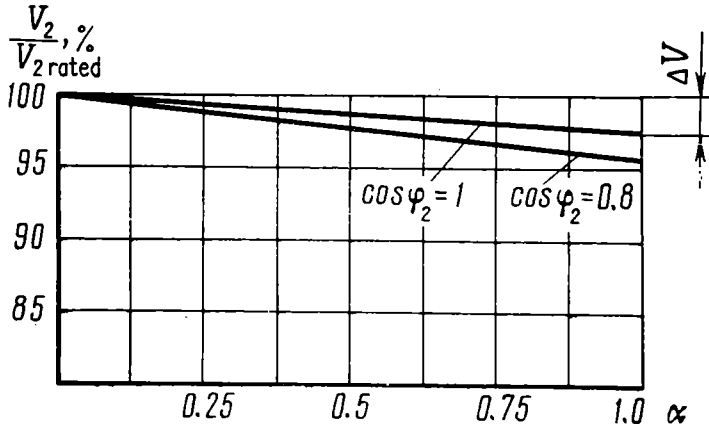


Fig. 6.3. Transformer output voltage regulation characteristic

The secondary load voltage V_2 differs from the open-circuit voltage by the amount of a voltage change which depends on the load value.

The output voltage regulation characteristic may be constructed both from the computed data on resistance and inductance drops (computed voltage regulation characteristic) and from the experimental data (characteristic of a particular transformer). Construction of the voltage regulation curve is shown in Fig. 6.3. The secondary voltage V_2 is plotted on the ordinate axis and the load value α is plotted on the abscissa axis (in per cent or decimal fractions of the rated power). The origin of the curve starts from the ordinate which equals $V_{2 \text{ rated}}$ while the other end of the curve,

opposite the abscissa $\alpha = 1$ (i.e., at the rated load), is lowered against the origin by the value ΔV which is a voltage change.

In view of the fact that the change in voltage is proportional to the load current I_2 (see (6.6) above), the voltage regulation characteristic will be represented by a straight line. Plotted in Fig. 6.3 are two voltage regulation curves, one for $\cos \varphi_2 = 1$ and the other for $\cos \varphi_2 = 0.8$.

Positions of these curves depend on the power and conditions of transformer load; at low power the curves may interchange their positions (at resistive and inductive-reactive loads).

6.3. Efficiency

The efficiency η of the transformer, as that of any energy converter, is the ratio of the useful power output to the power input, or, otherwise, the ratio of the secondary power P_2 of the transformer to its primary power P_1 expressed in per cent. Thus

$$\eta = \frac{P_2}{P_1} \cdot 100\%$$

In view of the high efficiency of the transformer (from 95 to 99.5% depending on the kVA rating), the values P_1 and P_2 do not differ materially. Therefore, for a more accurate computation of the transformer efficiency to be achieved, it is expedient to assume that the primary power equals the secondary plus the transformer total losses

$$P_1 = P_2 + P_o + P_{sc}$$

Substituting this into the initial formula of efficiency gives

$$\begin{aligned} \eta &= \frac{P_2}{P_1} \cdot 100 = \frac{P_2}{P_2 + P_o + P_{sc}} \cdot 100 = \\ &= \left(1 - \frac{P_o + P_{sc}}{P_2 + P_o + P_{sc}} \right) \cdot 100\% \end{aligned} \quad (6.7)$$

On the one hand, the above efficiency equation reduces the calculation errors and, on the other hand, it enables the ready-made transformer efficiency to be determined from the known losses, measured during the open-circuit and short-circuit tests, without measuring its primary and secondary

power, which, in most cases, would be totally impracticable.

The selection of the correct efficiency rating of the transformer being designed is not so simple as it might seem at a glance. When designing a transformer (or series of transformers) a compromise is inevitable: on the one hand, the reduction in transformer costs calls for a minimum expense of ferromagnetic and conductor materials, on the other hand, the quest for higher efficiencies and, thereby, for more economical transformers necessitates an increased consumption of these materials.

Therefore, the values of efficiency are established by standards specifying transformer losses. The transformer efficiency is specified on the basis of numerous national-economy factors, such as the cost of transformer materials, of electric power, of transmission lines, and also on the basis of past experience in the manufacture and use of transformers. Furthermore, it should be emphasized that a correct choice of the transformer efficiency is not yet enough to determine the amount of the transformer active components to be used. To build a most economical transformer of a given efficiency, it is necessary to consider the transformer load demand which is an influencing factor in determining the most rational relation between the open-circuit and short-circuit losses of the transformer.

This problem is extensively treated in Reference 2.

The transformer load demand varies over a wide range during the day and seasons of the year, depending on the consumer's demands. These variations are expressed in different daily, yearly and other transformer load demand charts. (One of these is shown in the Introduction, in Fig. 2.)

The transformer efficiency varies with load demand and therefore the transformer should be so constructed as to assure the highest efficiency at the most recurrent load demand.

The transformer load, i.e., effective power P_2 delivered on its secondary side, can be expressed as

$$P_2 = \alpha P \cos \varphi_2$$

where α is the transformer load factor expressed in fractions of rated power P ; $\cos \varphi_2$ is the power factor determined by the nature of load (lagging or leading).

The open-circuit losses P_o are proportional to the square of induction B but since the induction is proportional to the electromotive force E_1 , i.e., to the value which varies little with a change of load (when calculating a power transformer, it is common to assume that $E_1 \approx V_1$), the open-circuit losses may be practically regarded as *constant* at any load, i.e., $P_o = \text{const.}$

The short-circuit losses P_{sc} , both the main electrical and the stray losses, are proportional to the square of the load current I_2 . These losses are sometimes referred to as the *variable* losses. Consequently, the short-circuit losses for any load α may be expressed as

$$P_{sc} = \alpha^2 P_{sc, rated}$$

where the $P_{sc, rated}$ is the short-circuit losses at rated load.

In the above expression the no-load current in the primary and variations of the winding resistance with temperature are usually ignored since these factors affect but little the efficiency.

Substituting the obtained values of P_2 and P_{sc} in the main formula 6.7 yields the general efficiency formula true for any value of α

$$\eta = \left(1 - \frac{P_o + \alpha^2 P_{sc}}{\alpha P \cos \varphi_2 + P_o + \alpha^2 P_{sc}} \right) 100\% \quad (6.8)$$

The above-mentioned assumptions made to simplify the calculations and embodied in the formula do not appreciably affect the accuracy of calculations. These assumptions are also considered in the transformer standard specifications.

6.4. Conditions for Obtaining the Highest Efficiency

Applying the main formula for the transformer efficiency, we can find the conditions affording us to obtain the highest efficiency.

Taking the value of α as an independent variable, let us find the maximum value of function η . To do this, we should

first find the first derivative and reduce it to zero

$$\begin{aligned}\eta &= \left(1 - \frac{P_o + \alpha^2 P_{sc}}{\alpha P \cos \varphi_2 + P_o + \alpha^2 P_{sc}}\right) 100 = \\ &= \frac{\alpha P \cos \varphi_2}{\alpha P \cos \varphi_2 + P_o + \alpha^2 P_{sc}} \cdot 100 \\ \frac{d}{d\alpha} \eta &= \\ &= \frac{(\alpha P \cos \varphi_2 + P_o + \alpha^2 P_{sc}) P \cos \varphi_2 - \alpha P \cos \varphi_2 (P \cos \varphi_2 + 2\alpha P_{sc})}{(\alpha P \cos \varphi_2 + P_o + \alpha^2 P_{sc})^2} = 0\end{aligned}$$

The numerator will be zero because the denominator of the derivative is not infinity.

By removing the brackets we have

$$\begin{aligned}\alpha P^2 \cos^2 \varphi_2 + P_o P \cos \varphi_2 + \alpha^2 P_{sc} P \cos \varphi_2 - \alpha P^2 \cos^2 \varphi_2 - \\ - 2\alpha^2 P_{sc} P \cos \varphi_2 = P_o P \cos \varphi_2 - \alpha^2 P_{sc} P \cos \varphi_2 = 0\end{aligned}$$

Whence, $P_o = \alpha^2 P_{sc}$ (for any $\cos \varphi_2$ value).

From this it follows that the efficiency reaches its peak value when the short-circuit losses $\alpha^2 P_{sc}$ become equal to the open-circuit losses P_o .

Therefore, when designing a series of power transformers as well as individual ones, the relationship between the P_{sc} and P_o should be so selected for obtaining the highest average efficiency that $\alpha^2 P_{sc}$ and P_o can be approximately equal at the most typical load demand αP .

The open-circuit and short-circuit losses indicated in the power transformer standards have been selected on the basis of actual load-demand charts. The average value of α for the power transformer in service is about 0.45 to 0.55. Hence, from the above-given optimum equality $P_o = \alpha^2 P_{sc}$, it follows that the short-circuit losses should be 3.3 to 5 times as large as the open-circuit losses, i.e.,

$$\frac{P_{sc}}{P_o} = \frac{1}{(0.45 \text{ to } 0.55)^2} \approx 3.3 \text{ to } 5$$

It is advantageous to employ the power transformer with such a loss ratio at a more intensive load demand, i.e., with a more intensive utilization of its rated power output since its efficiency at a load from one half to the rated value decreases inappreciably as is shown in Fig. 6.4.

The flux density in the legs and yokes usually differs (refer to 4.3). However, it may be shown (this fact is not substantiated here) that with the same total weight of the core steel and proper core design, the open-circuit losses

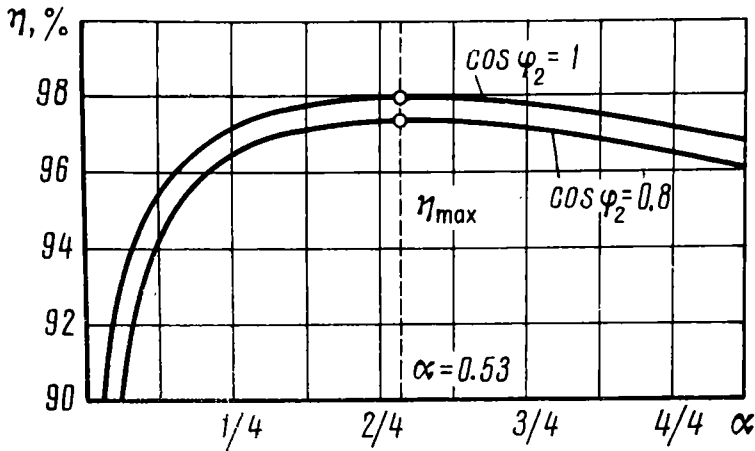


Fig. 6.4. Efficiency curves versus load and power factors

will be the smallest when the flux density values in the legs and the yokes are equal.

Similarly, the copper losses which constitute the main part of the short-circuit losses will be at a minimum if at a given common weight of the winding conductors the current density is approximately equal in the primary and secondary windings.

These circumstances should be considered in order to obtain the highest possible efficiency at the same weight of transformer active components.

Review Questions

1. Define the voltage regulation and write its formula.
2. What losses in the loaded transformer are regarded as constant and what losses are variable and why?
3. At which load is the highest efficiency obtained?

Additional Magnetic Flux Leakage and Mechanical Stresses

7.1. Nonuniform Distribution of Magnetomotive Forces

In deriving the reactance voltage drop formula (Sec. 5.5), it was assumed that the windings had a uniform distribution of the magnetomotive forces (ampere-turns) over their axial section and, accordingly, throughout the windings height.

In actual practice, however, at least one of the windings (HV) of a power transformer and occasionally both the win-

dings have a nonuniform distribution of ampere-turns. This is attributable to the following reasons.

1. Disconnection of a portion of the HV winding turns during tap changing.

The tap changing of the HV winding (this refers to $\pm 5\%$ or $\pm 2 \times 2.5\%$ of voltage adjustment range as given in

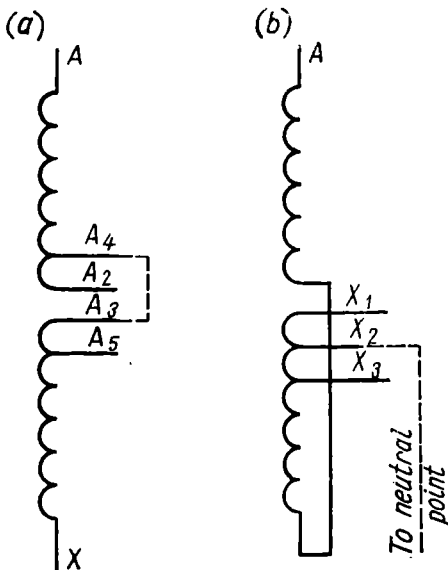


Fig. 7.1. HV winding tap changing schemes

standard specifications) is most commonly effected by use of two basic schemes, namely a centre-tap scheme with a break (Fig. 7.1a) and a scheme with near-neutral tapping (Fig. 7.1b). In both arrangements, the disconnected taps are in the middle of the windings.

In the direct-connected scheme, the switch (see Ch. Nine) connects taps A_3 and A_4 , say, on a nominal step (shown by

the broken line in Fig. 7.1a). Thus, the turns between the taps A_2 and A_4 are cut and therefore there is no magnetizing force in this winding portion.

In a similar fashion a tap X_2 is connected to the neutral point in the near-neutral tap scheme (used in a star connection) whereby the turns between taps X_1 and X_2 become disconnected.

Thus it follows that in the above voltage regulating schemes both on the nominal step and on minus 5 per cent,

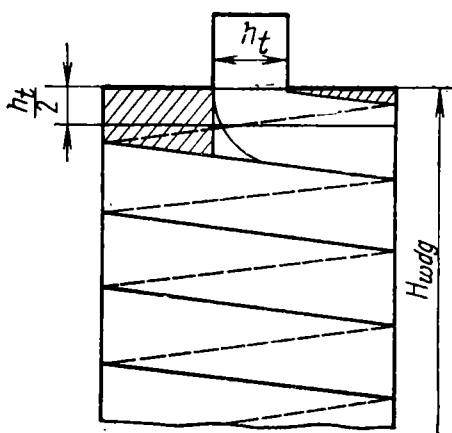


Fig. 7.2. Shortening of LV layer winding's effective height due to greater turn width

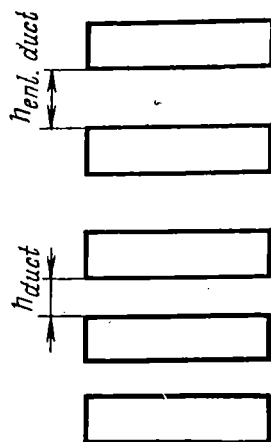


Fig. 7.3. Dispersion of ampere-turns of HV winding due to enlarged end ducts

the distribution of ampere-turns along the winding height is nonuniform due to the disconnection of a portion of the mid-turns.

2. Shortening of a layer (helical) winding height due to a greater width of the turn.

When calculating the axial size of the layer (or helical) winding (see Fig. 3.3), one turn was added to the number of turns in one layer due to the helical wind of the turns. However, at a greater width h_t of the turn, an empty space, free of a conductor material, is formed at the ends of the cylindrical (or helical) winding (hatched area in Fig. 7.2). As a consequence, the ampere-turns at the end of each winding occupy a smaller space, by approximately $h_t/2$.

3. Spacing of turns at certain points of the windings due to design considerations.

The end coils of the continuous winding with a service voltage of 35 kV and more have an added insulation of the turns and enlarged ducts $h_{enl. duct}$ between the coils, as is shown, for example, in Fig. 7.3. This leads to a greater dispersion (decreased density) of ampere-turns at these points and therefore to their nonuniform distribution.

The enlarged ducts at the points of group and common transpositions in the simplex helical winding are also responsible for the nonuniform distribution of ampere-turns.

The above-stated factors lead to unequal distribution (asymmetry) of the primary and secondary ampere-turns with winding height, which gives rise to an additional transverse leakage flux.

7.2. Calculation of Additional Reactance Drop Caused by Transverse Leakage Flux

Let us consider one of the most frequent cases of the asymmetric ampere-turn distribution, i.e., the disconnection

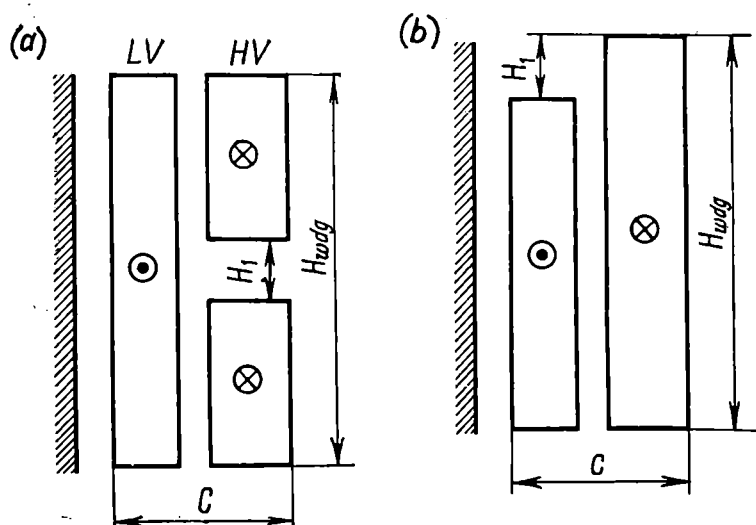


Fig. 7.4. Typical cases of nonuniform distribution of MMFs over winding height

of taps in the middle of the HV winding. Figure 7.4a shows an axial section of the windings and a distribution of the MMFs interrupted at H_1 in the middle of the HV winding.

The actual distribution of the MMFs in the HV windings may be represented in the form of two components, of which one will have the MMF identical to that of the main (HV) winding but uniformly distributed with height, while the other will possess a certain amount of additional MMF, as is shown in Fig. 7.5. Both MMFs must constitute, when added, an actual MMF of the HV winding.

Let us construct Kapp's diagram for these two components. The first component will be represented in the usual way,

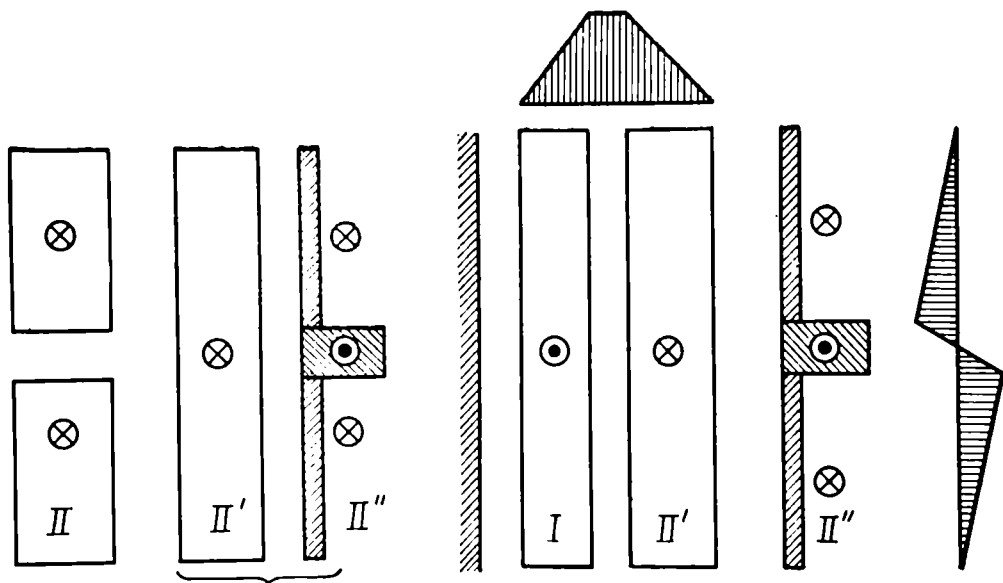


Fig. 7.5. Resolution of MMF of HV winding into main and additional components

Fig. 7.6. Kapp's diagrams for main (axial) and transverse leakage fluxes

i.e., as the one for the axial leakage field in the concentric windings. The reactance voltage drop for this pair of windings (HV and LV) is calculated by the known equation.

The diagram of the other component shown in Fig. 7.6 is turned through 90° so that it coincides with the additional transverse leakage flux. To create the transverse leakage flux, a certain additional amount of reactance voltage drop τ is required, which is expressed in per cent of the main voltage.

Thus the full reactance drop is

$$V_i = V_i' \left(1 + \frac{\tau}{100} \right) \% \quad (7.1)$$

where V'_l is the reactance voltage drop calculated by equation (5.8).

The additional reactance voltage drop τ may be also calculated with the aid of one of the approximate formulae depending on the location of the disconnected taps or dispersion of MMF:

(a) For the case when the turns are disconnected in the middle part of the HV winding:

$$\tau = \frac{100 \cdot H_1}{2H_{wdg}} \left(1 + \frac{\pi H_1}{2c} \right) \quad (7.2)$$

(b) For the case when the concentric or helical LV winding is shortened (at one end) due to a greater width H_1 of the turn (Fig. 7.4b):

$$\tau = \frac{100 \cdot H_1}{2H_{wdg}} \left(1 + \frac{\pi H_1}{c} \right) \quad (7.3)$$

Quantities H_{wdg} , H_1 and c entering into the above equations are given in Fig. 7.4a and 7.4b.

7.3. Mechanical Stresses

Interaction of magnetic leakage flux and the current through the winding gives rise to mechanical stresses in the winding. Under the normal operating conditions, when the transformer's load does not exceed the nominal value, these mechanical stresses do not present a serious hazard to the windings. However, in the case of sudden short-circuits, when the inrush steady-state current reaches a value of 20 to 25 times in excess of the rated value, the electromotive force, proportional to the square of the current, rises as much as 400 to 600 times. The instantaneous value of the current (see below) can still be twice the above-given value due to a free current component, causing appreciable damage to the transformer. Therefore, the transformer windings and the carrying parts should be so constructed as to withstand the mechanical stresses thus created.

As is known, the current-carrying conductor placed in a magnetic field and cutting the magnetic lines sustains a force applied to this conductor. This force is directed perpendicular to the direction of current and magnetic lines (left-hand rule).

Interaction of two current-carrying conductors is a sequel of this phenomenon. Two parallel conductors with uni-directional currents tend to attract each other (Fig. 7.7a)

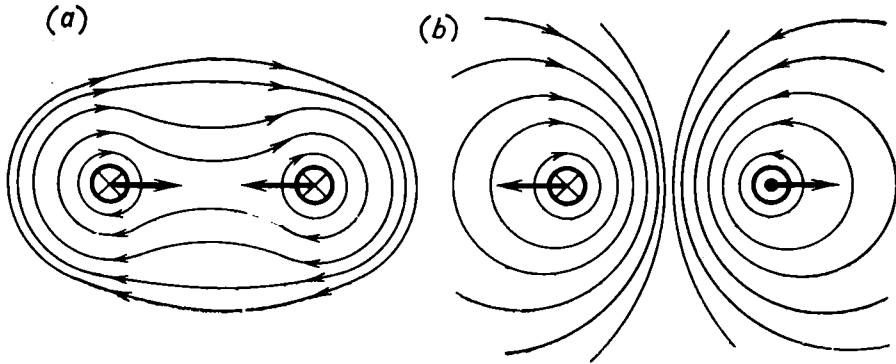


Fig. 7.7. Mechanical interaction between conductors and current while the conductors with oppositely directed currents repel each other (Fig. 7.7b).

These are the phenomena that occur in the transformer windings. The turns of one and the same winding tend to

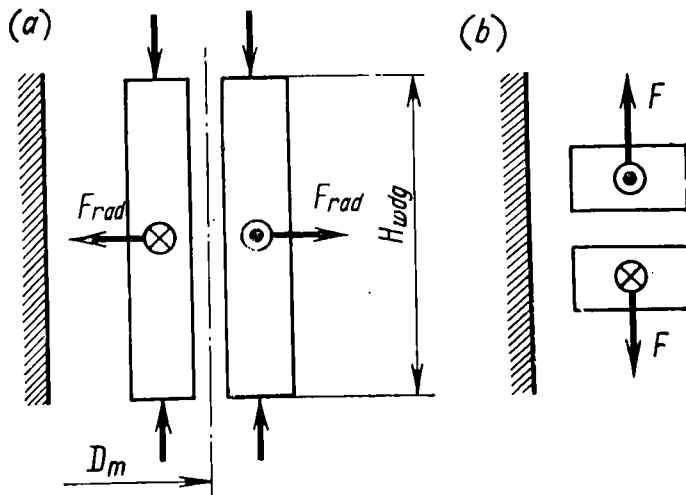


Fig. 7.8. Direction of mechanical stresses created in transformer windings

draw closer together causing the entire winding to contract, while the transformer's primary and secondary windings carrying oppositely directed currents tend to repel each other as is shown in Fig. 7.8a (concentric or symmetrical windings) and in Fig. 7.8b (sandwich disc windings).

7.4. Calculation of Radial and Axial Mechanical Stresses

In the concentric windings, due to the interaction of the currents through the primary and secondary windings, the outer winding tends to expand and the inner to contract. As a result, radial stresses arise in the windings acting on the conductors which resist these stresses.

The maximum radial stress F_{rad} caused by the interaction of the primary and secondary currents (see Fig. 7.8) is

$$F_{rad} = 12.8 (IN)^2 \frac{\pi D_m}{H_{wdg}} \cdot 10^{-8} \text{ kg} \quad (7.4)$$

where IN = MMF in one of the windings, A

D_m = medium diameter of the main leakage path, cm

H_{wdg} = height of the winding, cm

In case of short circuit, stress F_{rad} rises as the square of the inrush current value. Besides, at the initial stage of short circuit the mechanical stress is increased due to a constant component of current allowed for by the coefficient K_m .

Thus, the radial stress at the instant of shorting is

$$F_{rad. sc} = F_{rad} K_m^2 \left(\frac{100}{V_{sc}} \right)^2, \text{ kg} \quad (7.5)$$

where V_{sc} is the impedance voltage in %. Then

$$K_m = 1 + e^{-\pi \frac{V_R}{V_l}}$$

where V_R and V_l are the resistance and reactance components of the impedance voltage V_{sc} in %.

As already stated, the turns, carrying the unidirectional currents in each of the windings, tend to attract one another. Obviously, the maximum force in this case will be sustained by the turns positioned in the centre of the winding because exactly in this midpoint the forces exerted on each turn will be summed up. The axial stress thus produced may be approximately given as

$$F'_{ax} = F_{rad} \frac{\Delta}{2H_{wdg}}, \text{ kg} \quad (7.6)$$

where Δ is the width of the effective leakage path in cm.

In case of an asymmetric arrangement of the current-carrying turns throughout the height of one winding with respect to the turns in the other, a transverse magnetic flux appears, as was mentioned above. Consequently, an additional axial stress F''_{ax} is produced which is so directed that it tends to increase the present asymmetry.

The additional axial stress value depends upon the value of the lateral leakage flux, the exact calculation of which is difficult because the pattern of this flux is unknown.

The estimated length of transverse leakage flux H_l may be taken

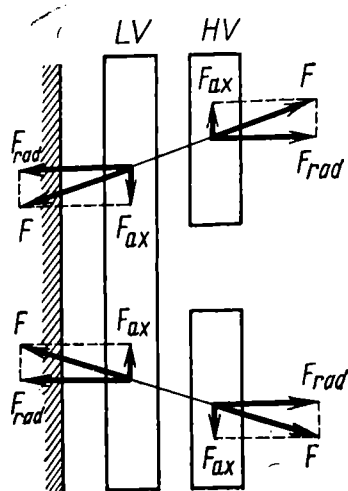


Fig. 7.9. Axial stresses arising due to asymmetrical position of MMFs in concentric windings

to be approximately equal to the length extending from the core leg to the tank wall on the assumption that the remaining portion of the leakage flux is closed through the transformer steelwork and therefore encounters a relatively low reluctance in these points.

If so, the additional axial stress will be

$$F''_{ax} = F_{rad} \frac{H_l}{H_l K_R m} \quad (7.7)$$

where m is the multiplier determined by the nature of asymmetry; $m = 1$ when the turns are lacking on only one end of a winding (shortening of the LV winding height by H_l) and $m = 4$ when the voltage regulating turns are disconnected at the centre of an HV winding or in case of shortening of an LV winding by $H_l/2$ on both sides.

The total axial stress F_{ax} (Fig. 7.9) for each winding will be equal to the sum or difference of both components, depending on the asymmetry in each winding.

In the case of a most commonly used two-sided shortening of the LV winding height (be it cylindrical or helical winding) and a disconnection of the regulating turns in the centre

of the HV winding, the total axial stress will be equal to the sum (for the LV winding) or difference (for the HV winding) of the main and additional axial stresses, i.e.,

$$F_{ax} = F'_{ax} \pm F''_{ax}, \text{ kg} \quad (7.8)$$

It should be pointed out that for the LV winding this is a compressive force with its peak value at the centre of the winding, and for the HV winding this is an expansive force acting through the yoke insulation on the yoke bars.

This is why the strength of the yoke clamping bars should be calculated so as to withstand such force.

As far as the windings are concerned, the mechanical stresses in the turns and in spacers should be determined by correlating them with the permissible specified values.

Review Questions

1. What is the transverse leakage flux and how does it arise?
2. What are the causes of mechanical stresses in the transformer windings?
3. What stresses arise in the windings and other parts of a transformer and under what conditions do they become hazardous?

Chapter Eight

Calculation of Special Transformers

8.1. Autotransformers. Distribution of Currents Through Winding Branches. Standard Capacity

The *autotransformer* is by definition a transformer consisting of only one winding with a part of its turns being common to both primary and secondary circuits.

The internal behaviour and the no-load working of an autotransformer are not different from those of an ordinary two-winding transformer.

Yet, there are certain specific features as regards the calculation of autotransformer parameters under load conditions when the load currents become so distributed in the winding that the current flowing through the common portion of the winding is equal to the difference between the primary and secondary load currents. Owing to this, the standard (rated) power of an autotransformer is less than the throughput power (the so-called auto-fraction) and therefore the autotransformers have the advantages of lower cost and smaller size over ordinary transformers although the degree of economy depends upon the transformation ratio as we shall see below.

The autotransformers, like the ordinary transformers may function as step-up and step-down transformers. By way of example, let us discuss a single-phase step-down autotransformer circuit (Fig. 8.1).

Let us place the winding with N_1 turns on the conventional closed core of a transformer and tap it so as to have N_2 turns between the tap and the start of the winding.

When the primary voltage V_1 is applied to the winding with N_1 turns, a secondary voltage V_2 is developed across the winding portion with N_2 turns. The secondary voltage of the autotransformer may be determined in the same

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When the primary voltage V_1 is applied to the winding with N_1 turns, a secondary voltage V_2 is developed across the winding portion with N_2 turns. The secondary voltage of the autotransformer may be determined in the same

manner as for an ordinary transformer by the general formula for the transformation ratio K (neglecting voltage drops)

$$K = \frac{N_1}{N_2} = \frac{V_1}{V_2}$$

Hence,

$$V_2 = V_1 \frac{N_2}{N_1} = N_2 e_N$$

To understand the distribution of load currents in the winding, it is necessary to consider autotransformer load conditions.

When the load Z_{load} is connected to the winding on the output side of the autotransformer, as is shown in Fig. 8.1,

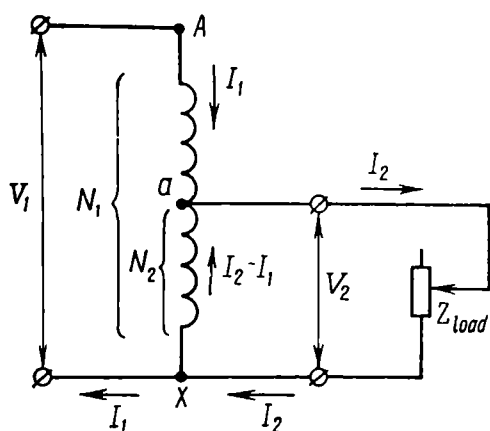


Fig. 8.1. Schematic diagram of single-phase autotransformer on load

a load current I_2 flows through the secondary circuit and a certain fraction of power $P_2 = V_2 I_2$ is consumed. This power fraction is referred to as the *throughput power* (or the *auto-fraction*), which is equivalent to the rated power P of the autotransformer. Neglecting the energy losses in the autotransformer, the primary power P_1 delivered by the supply network must be equal to P_2 (according to the law of energy preservation). The primary power P_1 produces a load current I_1 in the primary circuit.

Consequently

$$P_1 = V_1 I_1 = V_2 I_2 = P_2$$

The winding tap divides the winding at point a into an $a - X$ branch common for both primary and secondary circuits and an $A - a$ series branch. Let us now determine the load currents through each branch.

As is apparent from Fig. 8.1, current I_1 flows through series branch $A - a$. Current I_{a-x} of the common branch is equal to the phasor sum of currents I_1 and I_2 which are in opposition (see Sec. 5.1). Therefore, neglecting the no-load current, the I_{a-x} current is equal to the numerical difference between the secondary and primary load currents, i.e., $I_{a-x} = I_2 - I_1$ ($I_2 > I_1$) because this is a step-down autotransformer. As the figure shows, the currents through the common and series branches are opposite-directed.

It can be seen that the powers P_{A-a} and P_{a-x} in both branches of the winding are equal.

In the series branch

$$P_{A-a} = (V_1 - V_2) I_1 = V_1 I_1 - V_2 I_1$$

and in the common branch

$$P_{a-x} = V_2 (I_2 - I_1) = V_2 I_2 - V_2 I_1$$

Since $V_1 I_1 = V_2 I_2$, it can be readily observed that $P_{A-a} = P_{a-x}$.

The same is true for a step-up autotransformer.

In view of the fact that the series and common branches of the winding are equal in power and their MMFs are opposite-directed, the above branches may be looked upon as the primary and secondary windings of the transformer which has a certain capacity equal to the power of each branch. This is the standard or rated capacity of the autotransformer. *The standard capacity of the autotransformer* is the power transferred from the primary into the secondary circuit by way of electromagnetic induction. Thus only a portion of the power delivered to the primary is transformed electromagnetically, while the remaining part is passed over to the secondary directly through a resistive coupling between both the circuits.

An outstanding feature of the autotransformer is that its standard capacity is always less than the throughput power, owing to which the autotransformer of the same capacity as the ordinary two-winding transformer is always less costly.

The ratio of the standard capacity to the throughput power is termed the *autotransformer economy factor* K_e .

In the case of a step-down autotransformer ($V_1 > V_2$)

$$K_e = \frac{P_{st}}{P_{throu}} = \frac{(V_1 - V_2) I_1}{V_1 I_1} = \frac{V_1 - V_2}{V_1} = 1 - \frac{1}{K} \quad (8.1)$$

and for the step-up transformer ($V_2 > V_1$)

$$K_e = \frac{P_{st}}{P_{throu}} = \frac{(V_2 - V_1)}{V_2} = 1 - \frac{1}{K}$$

where K is the transformation ratio (HV to LV voltage ratio).

The autotransformer economy factor may be also defined as the difference between the primary and secondary voltages related to the highest of the two. This means that the standard capacity of an autotransformer, which determines its size and also the weight of its active components may be $1/K_e$ times less than the throughput power.

However, a tangible effect in terms of economy of active components when using an autotransformer instead of an ordinary transformer is achieved only at transformation ratio K near unity, as is seen from the above formula for K_e .

For a step-down transformer with a voltage ratio of 220/127 V, i.e., $K = 1.73$

$$K_e = \frac{220 - 127}{220} = 0.42$$

This means that the standard kVA rating of such an autotransformer will be merely 0.42 of its throughput power.

In the case of a greater voltage ratio, say,

$$K = \frac{20,000}{400} = 50$$

when the economy factor

$$K_e = \frac{20,000 - 400}{20,000} = 0.98$$

we gain almost nothing by using an autotransformer.

Furthermore, at high values of K the use of the autotransformers is hardly justified at all, for since primary and secondary circuits are electrically coupled, the insulation level of the LV circuit (without earthed neutral) and of all the electrical devices, machines and apparatus connected to this circuit must be the same as that for the HV circuit,

which is altogether undesirable. Besides, from the viewpoint of electrical safety, it is impermissible to connect *LV* circuits exposed to human body with *HV* circuits.

In view of the above considerations, the use of autotransformers is confined mainly to those cases when it is required to change the voltage within a small range and when the same voltage class may be tolerated both in the primary and secondary circuits.

Large autotransformers employ a three-winding design in accordance with appropriate standard specifications. In this case the *HV* and *MV* windings are connected in an autotransformer circuit arrangement, with the *LV* tertiary iso-

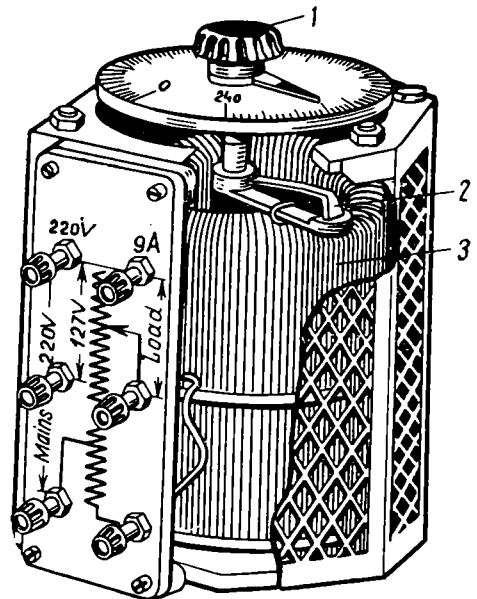


Fig. 8.2. Regulating autotransformer
1—control knob; 2—brush holder; 3—winding

lated, i.e., not connected with the *HV* and *MV* windings. The *LV* tertiary in the three-phase autotransformer is connected in delta to suppress the 3rd harmonic of the magnetic flux.

Three-winding autotransformers are employed in distribution substations where they are connected to three electric transmission lines with different voltages.

The tapped autotransformers are especially convenient for voltage adjustment. One of such autotransformers, type PHO is shown in Fig. 8.2.

8.2. Arrangement of Autotransformer Windings on Core Legs

As has been already mentioned, the series and common portions of the autotransformer should be viewed as the primary and secondary windings of a conventional transfor-

mer. This should be accounted for when arranging the windings on the core legs to avoid the generation of an excessively high leakage flux.

In the autotransformer with one leg carrying the windings (shell-type transformer), the turns of each winding section

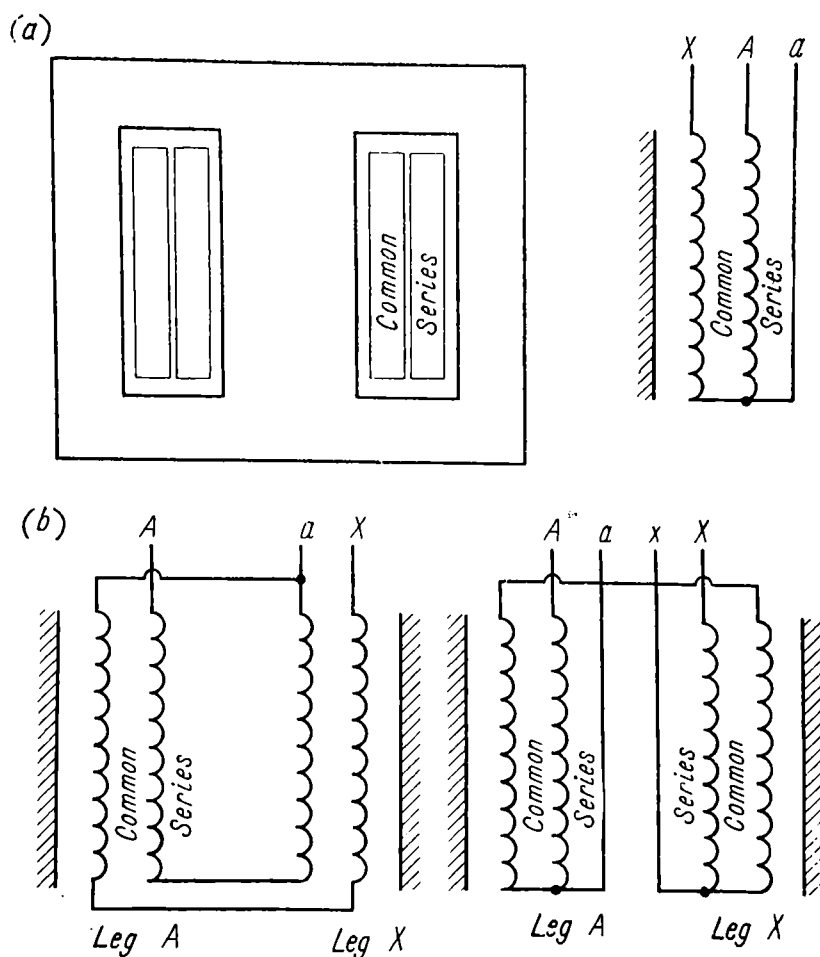


Fig. 8.3. Arrangement of autotransformer windings
(a) shell-type; (b) and (c) core-type

should be distributed along the height of the core (Fig. 8.3a), while in case of two legs used, the turns of each section should be distributed evenly on both legs (Fig. 8.3b, c).

8.3. Three-Phase Autotransformers

The windings of a three-phase autotransformer are placed onto a conventional magnetic core. Each branch of the wind-

ing per phase (if the windings are laid concentrically) is distributed along the entire height of the core window (Fig. 8.4).

It is common practice to connect the three-phase autotransformers in star (this connection is indicated as Y-auto).

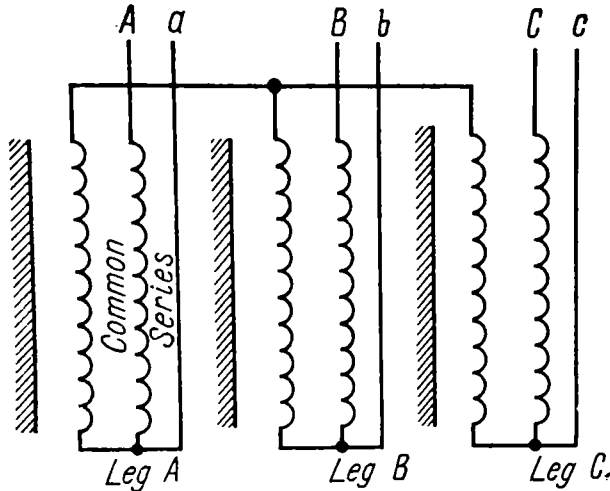


Fig. 8.4. Arrangement of three-phase autotransformer

Figure 8.5 shows a phasor diagram of a star-connected three-phase autotransformer.

The calculation of currents for each section of the winding is similar to that of a single-phase transformer.

The ratio of phase and line voltages will be exactly the same as that for three-phase star-star connected transfor-

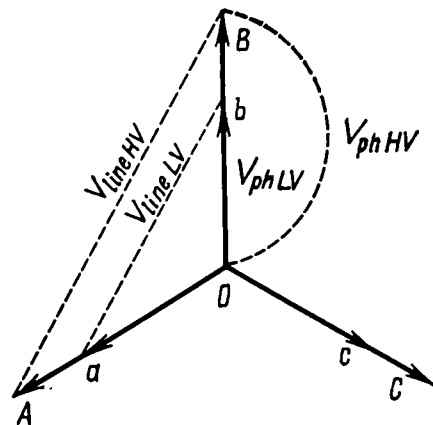


Fig. 8.5. Phasor diagram of three-phase autotransformer

mers. The phase voltages of HV and LV windings are $\sqrt{3}$ times as low as the respective line voltages.

In view of the above, the linear transformation ratio K_{line} is equal to the phase transformation ratio K_{ph}

$$K_{line} = \frac{V_{HV}}{V_{LV}} = -\frac{V_{ph. HV} \sqrt{3}}{V_{ph. LV} \sqrt{3}} = \frac{V_{ph. HV}}{V_{ph. LV}} = K_{ph}$$

where

$$K_{line} = \frac{AB}{ab} \text{ and } K_{ph} = \frac{AO}{aO}$$

The primary and secondary EMFs are phase coincident. As is apparent from the phasor diagram, the star-connected autotransformer has the connection group 0.

The standard capacity of the autotransformer is related to its throughput power by the same economy factor as for the single-phase autotransformer.

$$P_{st} = K_e P = \frac{V_{HV} - V_{LV}}{V_{HV}} P$$

8.4. Three-Winding Transformers. Basic Data. No-Load Conditions

With the distribution of electric energy, it is often necessary that the transformers should feed power to simultaneously two lines at different voltages. Under these circumstances it is more convenient and economical to use the capacity

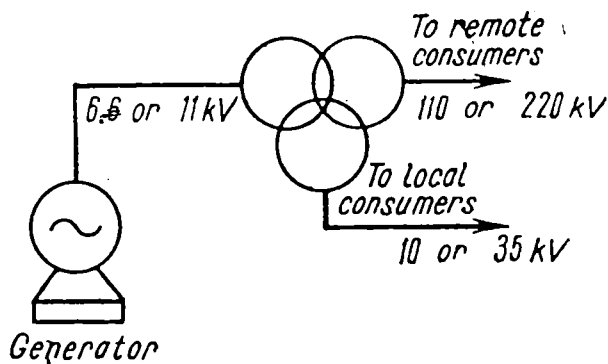


Fig. 8.6. Distribution of electric power through three-winding transformer

of a three-winding transformer instead of an equivalent bank of individual two-winding transformers with different transformation ratios. This also simplifies the construction of a transformer substation and reduces its cost.

An exemplary diagram of electric energy distribution by a three-winding transformer is given in Fig. 8.6.

Three-winding transformers have a high (HV), medium (MV), and low (LV) voltage winding.

According to the law of energy conservation, the primary power of the three-winding transformer must be equal to the sum of kVA in both secondary windings though the distribution of load power between these windings may vary.

The power transformer standards specify four groups of three-winding transformers according to their related powers (full or reduced) (Table 8.1).

The HV winding is always rated at full load, which is recognized as the power rating for the three-winding transformer. The three-winding transformer of group 1 indicated in the Table is designed to *operate at full load*, i.e., it affords the operation of any pair of its windings or the combination of all the three windings on full load. The remainder groups include the designs of transformers intended to operate at reduced rated power (up to 67 per cent) of the LV or MV winding or both. This reduces somewhat the cost of the transformer as the standard kVA rating decreases.

Table 8.1

Group	Power, %		
	HV	MV	LV
1	100	100	100
2	100	100	67
3	100	67	100
4	100	67	67

Considerations of design require that the HV winding should always be arranged on the outside of the leg in relation to the positions of MV and LV windings, which may be interchanged. Thus two winding arrangements are possible (in sequence from the inside to the outside): LV, MV, HV (Fig. 8.7a) and MV, LV, HV (Fig. 8.7b).

The terminal markings of the three-winding transformers according to power transformer standard specifications are given in Table 1.1.

The no-load condition of a three-winding transformer is basically the same as that of a conventional two-winding transformer.

For brevity, we shall indicate the HV, MV and LV windings through numbers 1, 2 and 3 (counting from the outer winding towards the inner winding, see Fig. 8.7a).

Should we connect one of the windings, say, winding 1 to the supply circuit with primary voltage V_1 , voltages V_2 and V_3 will be induced in windings 2 and 3.

Since the basic voltage formula

$$V = 4.44fN\Phi, \text{ V}$$

is true for each winding of the three-winding transformer, voltages V_2 and V_3

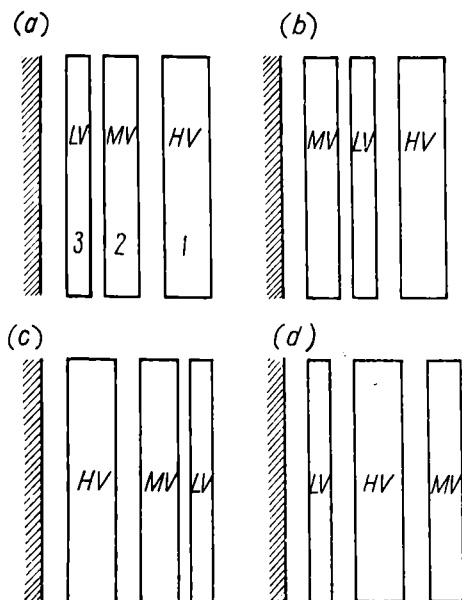


Fig. 8.7. Arrangement of windings on the core of a three-winding transformer

(a) LV winding, next to core; (b) LV winding between MV and HV windings; (c) and (d) unusable winding arrangements

will be proportional to the number of turns, N_2 and N_3 , in windings 2 and 3. In other words, the following relationships will be true for each winding:

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} = \frac{V_3}{N_3} = e_N$$

The voltage ratio or the transformation ratio of any pair of windings will be designated by letter K with a two-digit subscript, for instance,

$$\frac{V_1}{V_2} = K_{12}; \quad \frac{V_1}{V_3} = K_{13}; \quad \frac{V_2}{V_3} = K_{23}$$

The phenomena occurring in the two-winding transformers may be generalized and applied to the three-winding and other multi-circuit transformers.

As regards the three-winding transformer, the following EMF balance equation is true: $E_1 = E'_2 = E'_3$ or, neglecting the voltage drops, $V_1 = -V'_2 = -V'_3$. Thus the MMF

balance equation is

$$I_1 N_1 + I_2 N_2 + I_3 N_3 = I_0 N \approx 0$$

The subscripts of the above values are given under the assumption that winding 1 is primary.

The calculation of losses and a no-load current of the three-winding transformer does not differ from the calculation of these parameters for the two-winding transformer.

8.5. On-Load Conditions of Three-Winding Transformers. Calculation of Short-Circuit Losses and Impedance Voltage

The impedance voltage and short-circuit losses of the three-winding transformer, unlike those of the two-winding transformer, are specified and determined separately for each pair of the windings. Thus three values of V_{sc} and P_{sc} are determined for each transformer. To ensure uniformity of calculations, all values of V_{sc} and P_{sc} are conditionally referred to the full-load (100 per cent) rating even though one or two windings have been designed for the reduced (67 per cent) rating.

To determine the actual voltage drops and short-circuit losses at specified secondary kV ratings, appropriate recalculation is made. For this purpose, the voltage drops may be assumed to change in proportion to the power rating, whilst the short-circuit losses vary as the square of the power rating.

The reactance drops of any pair of windings, which almost equal the impedance voltages in high-power transformers, vary significantly due to different relative positions of the windings and different spacings between the windings, determined mainly by the width of the main leakage path.

The standards for the three-winding power transformers of voltage class 110-kV specify the following impedance voltages in per cent of rated voltage (determined basically by the reactance drops).

Between windings	1—2	10.5%
Same	2—3	6%
Same	1—3	17%

The reactance drop between windings 1 and 3 is greater because the main leakage path includes two spacings between

windings 1—2 and 2—3 as well as the radial size of winding 2.

Thus, the impedance voltages differ with each pair of the windings, depending on the sequence of their arrangement and the core position (Table 8.2).

Table 8.2

Between windings	Impedance voltage (per cent)	
	Fig. 8.7a	Fig. 8.7b
HV and LV	17	10.5
HV and MV	10.5	17
MV and LV	6	6

It is customary to employ the 2nd winding arrangement for a step-up three-winding transformer. In this case the primary (LV) winding is placed in the middle, i.e., in place of winding 2. As a result the voltage drop across the primary will be the least with respect to the other two secondary windings.

If both the secondaries are on load simultaneously, the leakage flux distribution (Kapp's diagram) will be more complicated than that for a two-winding transformer. The distribution diagram may be constructed as a sum of the diagrams for two leakage fluxes produced separately by two secondary fluxes.

The configuration of this diagram will vary depending on whether the primary is on the inside or in the middle.

Figure 8.8 gives the diagrams of the leakage fluxes for two cases: (a) when the primary is winding 1 (Fig. 8.8a) and (b) when the primary is winding 2 (Fig. 8.8b). The arrows indicate the direction of leakage fluxes in the spacings between the windings. The shaded sectors represent the geometric sums of the areas of the two diagrams.

8.6. Calculation of Voltage Drops in Windings of Three-Winding Transformer

It has already been stated that in the case of a three-winding transformer, three values of impedance voltage are

determined, each for the three pairs of windings. However, with the simultaneous loading of the two secondaries and various distribution of load between them it is next to

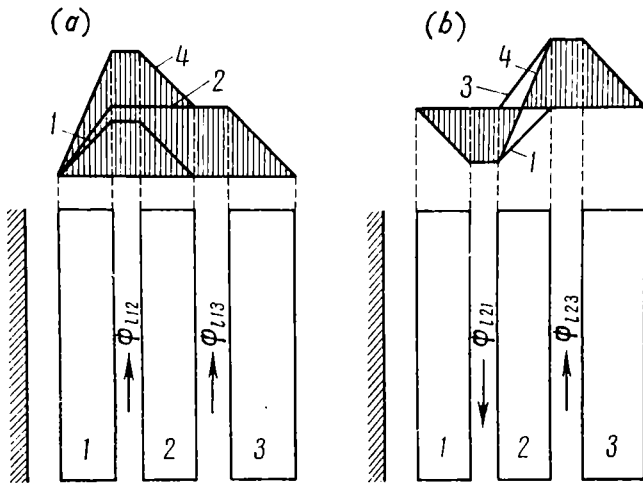


Fig. 8.8. Leakage flux diagrams of three-winding transformer
(a) primary 1; (b) primary 2; (1—leakage flux between windings 1 and 2; 2—leakage flux ϕ_{l13} ; 3—leakage flux ϕ_{l23} ; 4—total leakage flux)

impossible to determine the actual values of impedance voltage and voltage changes in each of them from the impedance voltage values only for pairs of windings.

In such an event recourse is made to determining the values of equivalent individual reactance drops and impedance voltages referred to each individual winding.

As each winding 1, 2 and 3 of the three-winding transformer has resistance R_1 , R_2 and R_3 respectively and consequently each winding has resistance drop V_{R1} , V_{R2} and V_{R3} , we may assume likewise that each winding has an inductive reactance X_1 , X_2 and X_3 and therefore an inductive drop V_{l1} , V_{l2} and V_{l3} (voltages induced by leakage fluxes).

The values of individual inductive drops cannot be measured directly in the ready-made transformer, though they can be determined by calculation from known values of voltage drops for each pair of windings either measured or computed on the basis of the known reactance drop formula given in Ch. Five.

The individual reactance drops in each winding of any pair of windings constitute the sum of the reactance drop in this pair:

$$V_{l1} + V_{l2} = V_{l12}$$

$$V_{l2} + V_{l3} = V_{l23}$$

$$V_{l1} + V_{l3} = V_{l13}$$

Calculating the above set of equations, we can easily obtain the following equations giving the inductive drops in each winding:

$$V_{l1} = \frac{V_{l12} + V_{l13} - V_{l23}}{2}$$

$$V_{l2} = \frac{V_{l12} + V_{l23} - V_{l13}}{2}$$

$$V_{l3} = \frac{V_{l13} + V_{l23} - V_{l12}}{2}$$

Thus, for the above-indicated values of the reactance drops in the winding pairs (Sec. 8.4) and for the 1st winding arrangement the values of individual reactance drops in each winding are the following:

$$V_{l1} = \frac{10.5 + 17 - 6}{2} = 10.75\%$$

$$V_{l2} = \frac{10.5 + 6 - 17}{2} = -0.25\%$$

$$V_{l3} = \frac{17 + 6 - 10.5}{2} = 6.25\%$$

As is apparent from this example, the individual reactance drops can also be negative.

8.7. Calculation of Regulation and Efficiency with Different Distribution of Load Between Secondaries of Three-Winding Transformer

A simplified phasor diagram may be useful to derive a formula of voltage regulation both for three-winding and two-winding transformers. Given below are the formulae

(without derivation) for determining voltage changes in each winding, i.e., individual voltage changes. Such a calculation method is more convenient for a three-winding transformer. These formulae are similar in appearance to the formula applied for two-winding transformers.

For winding 1

$$\Delta V_1 = \alpha_1 (V_{R1} \cos \varphi_1 \pm V_{I1} \sin \varphi_1) + \frac{\alpha_1^2 (V_{I1} \cos \varphi_1 \mp V_{R1} \sin \varphi_1)^2}{200}$$

where α_1 = load factor of the given winding expressed in fractions of the rated power

V_{R1} and V_{I1} = individual resistance and reactance drops

These formulae are also true for windings 2 and 3, with the only difference that the subscripts in the formulae are respectively changed.

The value of the voltage change for each of the pairs of windings is equal to the algebraic sum of the values of individual voltage changes.

Using the known quantities α_2 , α_3 , $\cos \varphi_2$ and $\cos \varphi_3$ for both the secondary windings (when winding 1 acts as primary), we can find parameters α_1 and $\cos \varphi_1$ for the primary winding:

$$\alpha_1 \cos \varphi_1 = \alpha_2 \left(\cos \varphi_2 + \alpha_2 \frac{V_{R2}}{100} \right) + \alpha_3 \left(\cos \varphi_3 + \alpha_3 \frac{V_{R3}}{100} \right)$$

$$\alpha_1 \sin \varphi_1 = \alpha_2 \left(\sin \varphi_2 + \alpha_2 \frac{V_{I2}}{100} \right) + \alpha_3 \left(\sin \varphi_3 + \alpha_3 \frac{V_{I3}}{100} \right)$$

$$\alpha_1 = \sqrt{(\alpha_1 \cos \varphi_1)^2 + (\alpha_1 \sin \varphi_1)^2}$$

It should be pointed out that the voltage regulation value in each of the winding pairs of the three-winding transformer also depends upon the amount and kind of load of the third winding and, consequently, the voltage regulation value will change with the load of the third winding.

Problem 8.1. Calculate the voltage drop of a 10,000-kVA three-winding transformer.

Winding 1	$V_{R1} = 0.2\%$	$V_{I1} = 6\%$
Winding 2	$V_{R2} = 0.2\%$	$V_{I2} = 0.3\%$
Winding 3	$V_{R3} = 0.25\%$	$V_{I3} = 10.8\%$

Let us make solutions for two variants of the problem:

Variant 1

$$\begin{aligned}\alpha_2 &= 0.6; & \cos \varphi_2 &= 0.8 \\ \alpha_3 &= 0.4; & \cos \varphi_3 &= 0.9\end{aligned}$$

The transformer is fully loaded ($\alpha_2 + \alpha_3 = 0.6 + 0.4 = 1$)
Determine the values of

$$\begin{aligned}\alpha_1 \cos \varphi_1 &= 0.6 (0.8 + 0.6 \times 0.002) + 0.4 (0.9 + 0.4 \times 0.0025) = \\ &= 0.841\end{aligned}$$

$$\begin{aligned}\alpha_1 \sin \varphi_1 &= 0.6 (0.6 + 0.6 \times 0.003) + 0.4 (0.44 + 0.4 \times \\ &\times 0.0108) = 0.539\end{aligned}$$

$$\begin{aligned}\alpha_1 &= \sqrt{0.841^2 + 0.539^2} = 1; & \cos \varphi_1 &= 0.841; \\ & & \sin \varphi_1 &= 0.539\end{aligned}$$

$$\Delta V_1 = 1 (0.2 \times 0.841 + 6 \times 0.539) = 3.41\%$$

$$\Delta V_2 = 0.6 (0.2 \times 0.8 + 0.3 \times 0.6) = 0.204\%$$

$$\Delta V_3 = 0.4 (0.25 \times 0.9 + 10.8 \times 0.44) = 1.99\%$$

$$\Delta V_{12} = \Delta V_1 + \Delta V_2 = 3.41 + 0.204 = 3.61\%$$

$$\Delta V_{13} = \Delta V_1 + \Delta V_3 = 3.41 + 1.99 = 5.4\%$$

Variant 2

$$\begin{aligned}\alpha_2 &= 0.3; & \cos \varphi_2 &= 0.8 \\ \alpha_3 &= 0.4; & \cos \varphi_3 &= 0.9\end{aligned}$$

The transformer is not fully loaded (the power of winding 2 is half the value given in Variant 1).

Determine the values of

$$\begin{aligned}\alpha_1 \cos \varphi_1 &= 0.3 (0.8 + 0.3 \times 0.002) + 0.4 (0.9 + 0.4 \times 0.0025) = \\ &= 0.6\end{aligned}$$

$$\begin{aligned}\alpha_1 \sin \varphi_1 &= 0.3 (0.6 + 0.3 \times 0.003) + 0.4 (0.44 + 0.4 \times 0.0108) = \\ &= 0.358\end{aligned}$$

$$\begin{aligned}\alpha_1 &= \sqrt{0.6^2 + 0.358^2} = 0.7; \\ \cos \varphi_1 &= 0.858; & \sin \varphi_1 &= 0.512\end{aligned}$$

$$\Delta V_1 = 0.7 (0.2 \times 0.858 + 6 \times 0.512) = 2.275\%$$

$$\Delta V_2 = 0.3 (0.2 \times 0.8 + 0.3 \times 0.6) = 0.102\%$$

$$\Delta V_3 = 0.4 (0.25 \times 0.9 + 10.8 \times 0.44) = 1.99\%$$

$$\Delta V_{12} = \Delta V_1 + \Delta V_2 = 2.275 + 0.102 = 2.38\%$$

$$\Delta V_{13} = \Delta V_1 + \Delta V_3 = 2.275 + 1.99 = 4.27\%$$

The above-given example of the two versions of loading the three-winding transformer shows that when the load

decreases only on one secondary winding 2, the voltage drop decreases also in the other secondary winding 3. This example illustrates the dependence of operating conditions of one winding on the amount of load on the other.

The efficiency of the three-winding transformer is determined from the sum of loads on both secondary windings by the formula similar to one used for calculation of the two-winding transformer efficiency

$$\eta = \left(1 - \frac{P_o + \Sigma P_{sc}}{P \cos \varphi_1 + P_o + \Sigma P_{sc}} \right) 100\%$$

$$\Sigma P_{sc} = \alpha_1^2 P_{sc1} + \alpha_2^2 P_{sc2} + \alpha_3^2 P_{sc3}$$

where P_o is the open-circuit losses, kW; P_{sc1} , P_{sc2} , P_{sc3} are the short-circuit losses (individual values for windings 1, 2, and 3), kW. The remaining nomenclature is the same as that used in the voltage regulation formula.

In an approximate form we can assume that

$$\cos \varphi_1 = \frac{\alpha_2 \cos \varphi_2 + \alpha_3 \cos \varphi_3}{\alpha_2 + \alpha_3}$$

Problem 8.2

Determine the efficiency of a three-winding transformer proceeding from the data given under Solution 8.1 for both load variants.

Additional data:

$$P_o = 14.5 \text{ kW}; \quad P_{sc1} = P_{sc2} = 20 \text{ kW}; \quad P_{sc3} = 25 \text{ kW}$$

Variant 1

$$\alpha_2 = 0.6 \quad \cos \varphi_2 = 0.8$$

$$\alpha_3 = 0.4 \quad \cos \varphi_3 = 0.9$$

$$\Sigma P_{sc} = (0.6 + 0.4)^2 20 + 0.6^2 \times 20 + 0.4^2 \times 25 = 31.2 \text{ kW}$$

$$\cos \varphi_1 = 0.841$$

$$\eta = \left[1 - \frac{14.5 + 31.2}{(0.6 + 0.4) 10,000 \times 0.841 + 14.5 + 31.2} \right] 100 = 99.46\%$$

Variant 2

$$\alpha_2 = 0.3; \quad \alpha_3 = 0.4; \quad \cos \varphi_2 = 0.3 \quad \cos \varphi_3 = 0.9$$

$$\Sigma P_{sc} = (0.3 + 0.4)^2 20 + 0.3^2 \times 20 + 0.4^2 \times 25 = 15.6 \text{ kW}$$

$$\cos \varphi_1 = 0.858$$

$$\eta = \left[1 - \frac{14.5 + 15.6}{(0.3 + 0.4) 10,000 \times 0.858 + 14.5 + 15.6} \right] 100 = 99.5\%$$

8.8. Design of Transformers Used for Feeding Mercury Rectifiers

In some branches of industry use is made of direct current as alternating current proves unsuitable due to various reasons. Thus, direct current is used in transport to feed traction motors and also in production workshops for various electrolysis processes, charging of storage batteries, etc.

Direct current is obtained for industrial use by way of AC rectification effected with mercury rectifiers which utilize the valve property of the electric arc glowing in vacuum.

Specific conditions should be provided to obtain this rectifying property. In recent years, semiconductor silicon-controlled rectifiers have been brought in wide use.

Thus, direct current is obtained by converting three-phase alternating current into so-called rectified current, i.e., unidirectional pulsating current which can be brought, by means of the filters and reactors, to nearly ideal constant current.

Due to the valve property of the mercury-arc rectifier the current of one of the phases of the secondary winding flows only during a portion of the cycle (through that rectifier anode on which the voltage is higher), and therefore the operating conditions of the primary and secondary windings of the rectifier transformer and their rated capacities are unequal.

The standard capacity P_{st} of the rectifier transformer is determined as half the sum of ratings P_1 and P_2 of the primary and secondary windings, i.e.,

$$P_{st} = \frac{P_1 + P_2}{2}$$

The mean value of the rectified voltage and the effective value of the alternating voltage of the secondary winding are interrelated in a definite manner depending on the number of phases and connection of the rectifier.

8.9. Single- and Poly-Phase Rectification Circuits Employing Mercury-Arc Rectifier and Transformer

Single-phase full-wave circuit. The transformer secondary is centre-tapped, the centre tap serving as the negative terminal of the rectified voltage V_{rect} . The ends of the secondary winding are brought to the anodes of the rectifier, the cathode of which is the positive terminal of the rectified voltage (Fig. 8.9a).

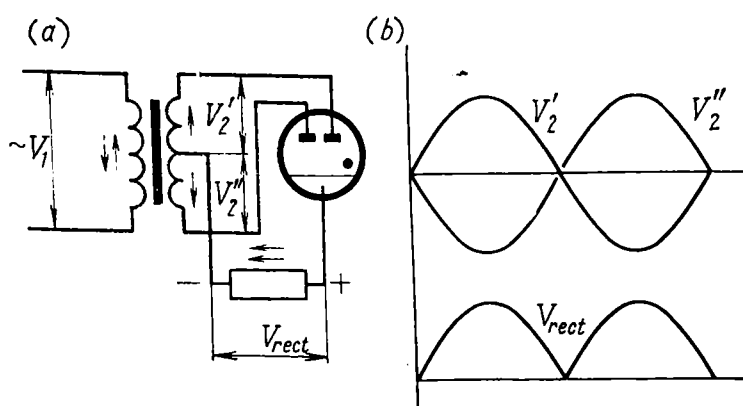


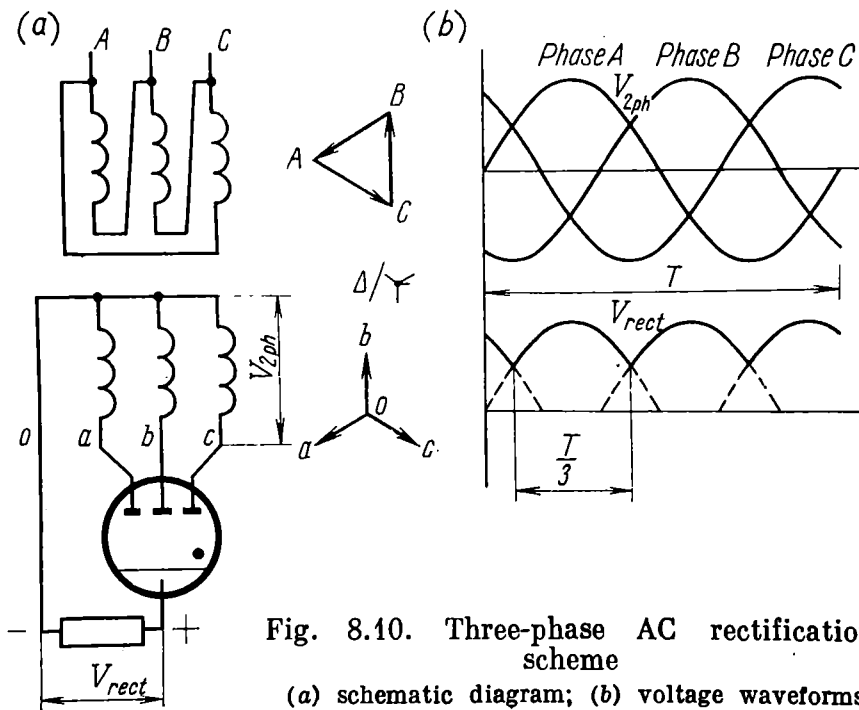
Fig. 8.9. Single-phase full-wave AC rectification scheme
(a) schematic diagram; (b) voltage waveforms

In this circuit, both halves of the secondary winding operate in alternation, a half-cycle each. This can be easily observed on the diagram, knowing that in the rectifier the current can flow in one direction only, namely, from the anode to the cathode. If, for instance, the voltage across the secondary winding is directed upwards, the current will pass only through the right-hand anode of the rectifier and will be then returned to the winding via the load circuit. There will be no current through the lower half of the winding because the circuit will be rendered non-conductive by the left anode. The next half-cycle will be inverted and the current will flow only through the lower half of the winding.

Consequently, the external load circuit will carry only a unidirectional current, that is, a rectified or direct pulsating current (Fig. 8.9b).

Delta-star connected three-phase rectifier transformer (with neutral connection). In the three-phase rectification circuit the line input terminals of the secondary winding are connected to three anodes of the rectifier, the neutral point being a negative terminal of the rectified voltage (Fig. 8.10a).

In this circuit, like in the other poly-phase circuits, the arc glows only at the anode which has the highest positive



potential and therefore the arc and the current are transferred every one-third of the cycle from one anode to the other. Thus, the anodes as well as the phases of the secondary winding function in alternation.

Hence, the transformer circuit should be so connected as to supply a single-phase load. The connections suitable for this purpose are:

$$\Delta/\text{Y} : \Delta/\text{Y} : \text{Y}/\text{Y}$$

The waveform of the rectified voltage in the three-phase connection has a smaller amplitude than in the full-wave

circuit. If in the full-wave circuit the voltage periodically drops to zero, in the three-phase circuit the minimum rectified voltage value constitutes half its peak amplitude (see Fig. 8.10b). Thus the three-phase rectification circuit produces a smoother waveform of the rectified voltage.

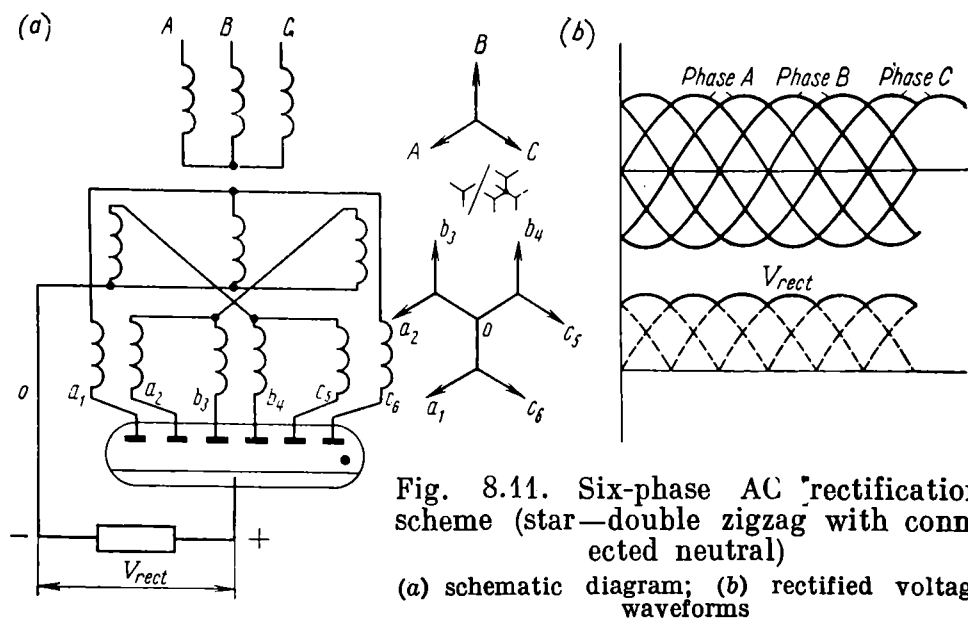


Fig. 8.11. Six-phase AC rectification scheme (star—double zigzag with connected neutral)

(a) schematic diagram; (b) rectified voltage waveforms

From this it follows, that an increased number of phases on the secondary side of the transformer provides for a better voltage waveform on the direct-current output side. That is why, six-phase rectification circuits have found an extensive application.

Six-phase rectification circuit with transformer windings connected in star—double zigzag, with neutral connection. A six-phase circuit may be obtained from a three-phase circuit by using an appropriate phase transformation connection on the secondary side of a transformer. One such connection of the secondary is a double zigzag shown in Fig. 8.11a.

Three coils are arranged on each leg of the three-phase transformer on its secondary side. All the coils have a similar number of turns (equal-branch zigzag). The coils forming the inner star have the wire section $\sqrt{2}$ times the section of the wires in the outer branches. This difference is due to

the fact that the secondary current passes through the branches of the inner star for one-third of the cycle, whereas it takes one-sixth of the cycle to pass through outer branches.

The lettering of the winding ends agrees with that of the transformer phases while the numerical subscripts show the anode number according to the operation sequence.

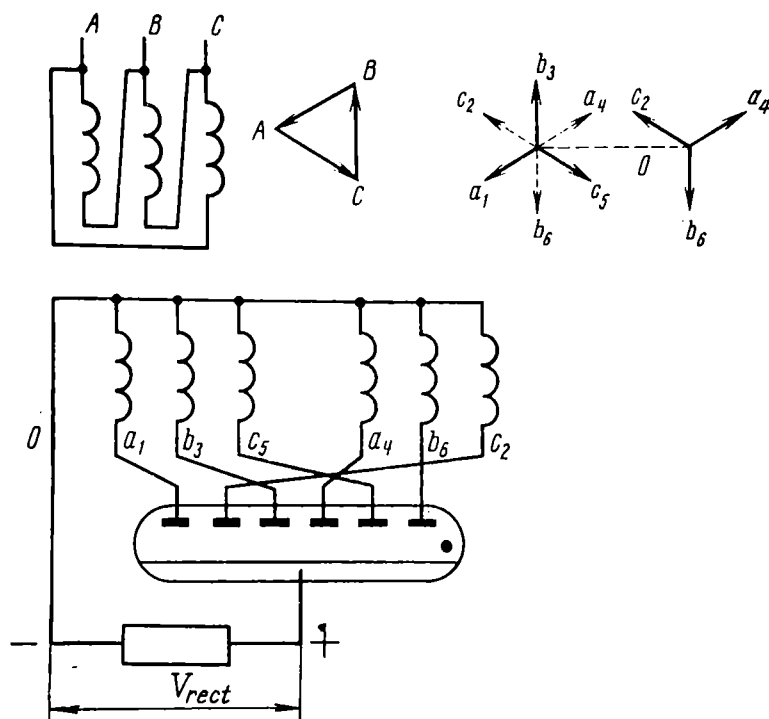


Fig. 8.12. Six-phase AC rectification scheme (delta—star—inverted star with neutrals)

(a) schematic diagram; (b) phasor diagram of secondary windings connected in two inverted stars

Figure 8.11b demonstrates a rectified voltage waveform in the six-phase circuit.

The primary may be connected both in star and delta since the secondary is always connected to two phases and, therefore, no phase distortion occurs.

Six-phase rectification circuit with transformer windings connected in delta—star—inverted star, with neutrals. Another six-phase circuit of the secondary winding connected in two stars is shown in Fig. 8.12a.

Each leg (phase) of the core carries two similar secondary windings, one being included into a star circuit (connection group 0) while the other, into an inverted (phase-shifted) star circuit (connection group 6), i.e., turned by 180° or by 6 angular units with respect to the former. This is attained either by a different direction of wind of the secondary windings or by a change in the terminal marking of one of the windings.

The phasor diagram in Fig. 8.12b shows that a six-phase transformation circuit may be obtained by superposition of two secondaries connected in two inverted stars.

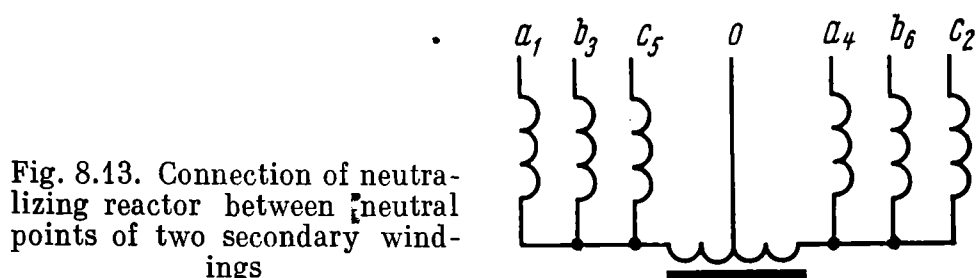


Fig. 8.13. Connection of neutralizing reactor between neutral points of two secondary windings

Since only one of the phases is loaded at all times during the rectifier operation, the primary winding must be delta-connected to avoid phase distortion entailing an increase in reactance drop.

The six-phase transformation circuit with two inverted star connections is usually provided with a neutralizing reactor interposed between the neutral points of both stars (Fig. 8.13). The purpose of the neutralizing reactor is to obtain a certain superposition of anode currents, which makes it possible to produce a smoother direct current waveform and an increased power output of the transformer bank. The presence of inductance in the anode circuit slows down the extinction of the arc when it is transferred to the next anode and, therefore, the current drops to zero gradually. Thus, the glow of two anodes is maintained for a certain period of time.

The six-phase circuit with two inverted-star connections and a neutralizing reactor is most commonly used with powerful rectifiers.

8.10. Determination of Mean Rectified Voltage

In designing the transformers intended to supply mercury rectifiers, a mean rectified voltage V_{rect} must be specified apart from other basic parameters. The secondary (phase) voltage V_{2ph} necessary for the calculation of winding data is determined on the basis of the mean rectified voltage value. The relationship between the mean rectified voltage and the phase voltage differs with the number of phases and chosen transformer connection.

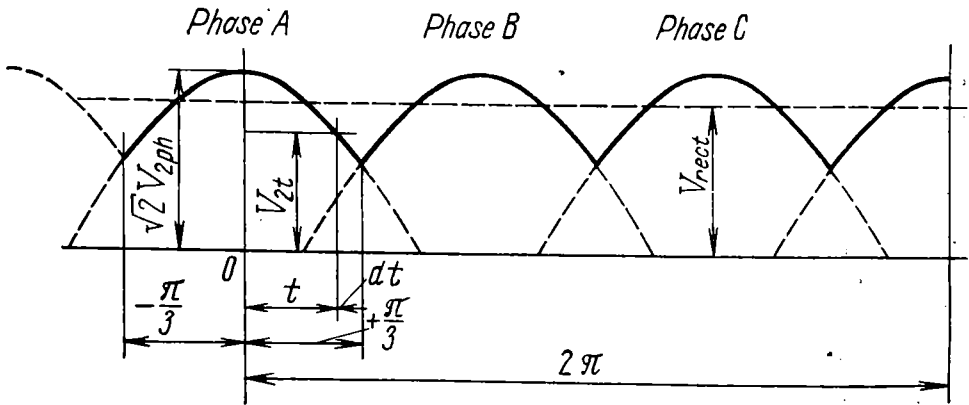


Fig. 8.14. Three-phase rectified voltage chart for calculation of secondary phase voltage

By way of example, let us consider a three-phase transformer and determine the relationship between the AC and rectified DC voltages.

The rectified voltage chart for a three-phase circuit is shown in Fig. 8.14.

Supposing the amplitude $\sqrt{2}V_{2ph}$ of phase A is the origin of coordinates. Then, at any instant t of the period (2π) the instantaneous value of the secondary voltage of phase A is

$$V_{2t} = \sqrt{2}V_{2ph} \cos t$$

As is obvious from the chart (see Fig. 8.14) the voltage in phase A is maintained within the time interval from $-\pi/3$ to $+\pi/3$, that is, the duration is two-thirds or one-third of the cycle. The mean rectified voltage value V_{rect}

will be equivalent to the middle ordinate of the waveform in the given portion.

$$\begin{aligned}
 V_{rect} &= \frac{\sqrt{2} V_{2ph}}{\frac{2\pi}{3}} \int_{-\frac{\pi}{3}}^{+\frac{\pi}{3}} \cos t dt = \\
 &= \frac{\sqrt{2} V_{2ph}}{\frac{2\pi}{3}} \sin t \Big|_{-\frac{\pi}{3}}^{+\frac{\pi}{3}} = \frac{\sqrt{2} V_{2ph}}{\frac{2\pi}{3}} \left[\sin \frac{\pi}{3} - \left(-\sin \frac{\pi}{3} \right) \right] = \\
 &= \frac{\sqrt{2} V_{2ph}}{\frac{2\pi}{3}} 2 \sin \frac{\pi}{3} = \sqrt{2} V_{2ph} \frac{\sin \frac{\pi}{3}}{\frac{\pi}{3}} = 1.17 V_{2ph}
 \end{aligned}$$

The obtained relationship is also true for a three-phase circuit (number of phases, $m = 3$).

It is quite obvious that for some other number of phases the above formula can be represented in the following general form:

$$V_{rect} = \sqrt{2} V_{2ph} \frac{\sin \frac{\pi}{m}}{\frac{\pi}{m}}$$

Hence,

$$\begin{aligned}
 \text{at } m = 2, V_{rect} &= 0.9 V_{2ph} \\
 \text{at } m = 6, V_{rect} &= 1.35 V_{2ph}
 \end{aligned}$$

8.11. Standard kVA Rating of Mercury-Arc Rectifier Transformers

Due to the alternate operation of phases of the rectifier transformer secondary winding (see Sec. 8.9), the transformer standard kVA rating is increased as compared to that of the power transformer of the same rated kVA.

Let us discuss a full-wave rectification circuit as the simplest (refer to Fig. 8.9).

The secondary current I_2 flows alternately through each half of the winding during the half-cycle.

The section of the wire used in the secondary winding should be determined by the effective value of a direct non-

pulsating current I_{2eff} which should be equivalent as to copper losses in the windings to the pulsating current I_2 . Thus, the following equality can be given

$$I_{2eff}^2 r_2 = \frac{1}{2} I_2^2 r_2$$

where r_2 = resistance of the secondary
 $\frac{1}{2}$ = factor allowing for passage of current I_2 during the half-cycle

Hence $I_{2eff} = I_2/\sqrt{2}$, i.e., the equivalent current which is the rated current for the secondary winding, will be $\sqrt{2}$ times less than current I_2 . However, this secondary winding requires $2/\sqrt{2}-\sqrt{2}$ times more of conductor material than the secondary winding of a power transformer of the same kVA rating at the same current density, because the winding consists of two halves, and, therefore, the transformer must have a greater standard kVA rating.

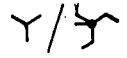
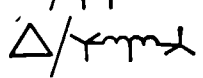
Thus the reason for the increased rating lies in the fact that both halves of the winding do not receive the current simultaneously.

Reasoning in a similar fashion, we can prove that in a general case at any number (m) of phases, the rated current for each branch of the winding will be $I_{2eff} = I_2/\sqrt{m}$.

Similarly, when the number of phases is two and more, the primary winding will require a greater amount of copper.

The increase in the standard kVA rating for the typical rectification circuits are given in Table 8.3.

Table 8.3

Number of phases	Connection	Ratings		
		P_2	P_1	P_{st}
3		$1.71P_{rect}$	$1.21P_{rect}$	$1.46P_{rect}$
6		$1.79P_{rect}$	$1.05P_{rect}$	$1.42P_{rect}$
6		$1.48P_{rect}$	$1.05P_{rect}$	$1.26P_{rect}$

P_1 , P_2 and P_{st} are the ratings of the primary and secondary, and the standard rating; P_{rect} is the rectified power.

In addition to the increase in the standard power of rectifier transformers caused by non-simultaneous phase loading, the standard rating should be further increased because of the following reasons.

The conductors used for secondary windings have an added wire insulation to guard against possible internal overvoltages caused by arc failures and backfires. Besides, on account of the overheating conditions associated with overloading, conductors of increased section are chosen.

The choice of a greater conductor section is also due to mechanical stresses that stem from the above causes.

This is also the reason why a greater number of spacers of a greater width (50 mm) are placed over the winding circumference.

Owing to the above reasons, the additional increase of the standard rating constitutes 10 to 15 per cent.

8.12. Smoothing Filters

On a number of occasions, for example, in radio engineering it is desired to obtain practically constant current, i.e., the current with minimum amplitude. In such circumstances

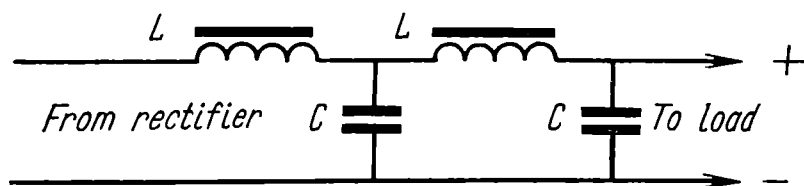


Fig. 8.15. Diagram of two-network smoothing filter

use is made of the so-called smoothing filters which remove the fluctuations of the rectified voltage.

The filter (Fig. 8.15) is composed of one or more networks consisting of capacitances and inductances (reactor filters).

The number of filter networks and the ratings of capacitance C and inductance L depend on the pre-set smoothing factor q_{sm} . The LC ratings are determined as follows:

$$LC = \frac{10 (Q_{sm} + 1)}{m^2}$$

where L = reactor inductance, henries

C = filter capacitance, μF

m = number of the rectifier phases

$q_{sm} = V_{in}/V_{out}$ = smoothing factor

V_{in} and V_{out} = amplitudes of the alternating voltage component at the filter input and output, V.

The filters attenuate a portion of voltage and dissipate a certain amount of energy, thereby reducing the total efficiency of the rectifier unit.

Review Questions

1. Define the autotransformer.
2. What are the throughput and standard powers of the autotransformer?
3. What are the limitations on the use of an autotransformer?
4. How should the windings be arranged on the autotransformer core legs?
5. In which cases are the three-winding transformers employed?
6. How are the three-winding transformer terminals marked?
7. Define the specific features of calculating the load conditions of the three-winding transformers.
8. Why are the polyphase circuits more preferable for the rectification of alternating current?
9. Why is the standard capacity of the rectifier transformer greater than that of the power transformer of the same rated kVA?

Chapter Nine

Tap Changing

9.1. General Requirements for Transformer Voltage Control

The necessity of regulating the transformer voltage or adjusting the transformation ratio arises in numerous cases due to a varying transformer duty. In the majority of cases (notably in the case of power transformers) this stems from the requirement for maintaining constant rated voltages at the consumer's supply points which may be close to or far away from the power stations and distribution substations. The voltages in each of the consumer's networks may vary appreciably. Besides, the consumers' voltages vary due to a change in the load on the networks. Owing to all this, supply voltages may go beyond the permissible limits specified in the national standard for voltage variation at consumers (-2.5 , $+5\%$ for lighting and -5% , $+10\%$ for electric motors).

Tap changing, i.e., increasing or decreasing of the number of active turns in one of the windings is the most wide-spread method of high-power transformer voltage control because of its simplicity and dependability. The number of active turns is changed by provision of the voltage-regulating tappings in the winding, enabling stepped voltage regulation. At the highest voltage all the turns of the winding are cut in whereas at a decreased voltage a portion of the turns is cut out.

The following voltage adjustment range (permissible percentage regulation) and the voltage regulating steps of the HV winding are given in the standard specifications:

1. For the transformers of 25 to 40,000 kVA using the off-circuit tap changing, the permissible percentage regulation is $\pm 2 \times 2.5\%$.

2. For the transformers of up to 630 kVA, the permissible percentage regulation is $\pm 5\%$ (under specified conditions).

3. The percentage regulation for the transformers with on-load tap changing equipment are indicated in Table 9.1.

Table 9.1

kVA rating	Voltage, kV	Percentage regulation and voltage regulating steps
63-630	6 and 10	$\pm 6 \times 1.67\%$
100-630	20 and 35	$\pm 6 \times 1.67\%$
1000-6300	6 and 10	$\pm 8 \times 1.25\%$
1000-6300	20 and 35	$\pm 6 \times 1.5\%$
10,000-63,000	35	$\pm 8 \times 1.5\%$

9.2. Off-Circuit Tap Changing

As has been already mentioned in Ch. Seven, the cut-out turns should be situated in the middle of the winding height.

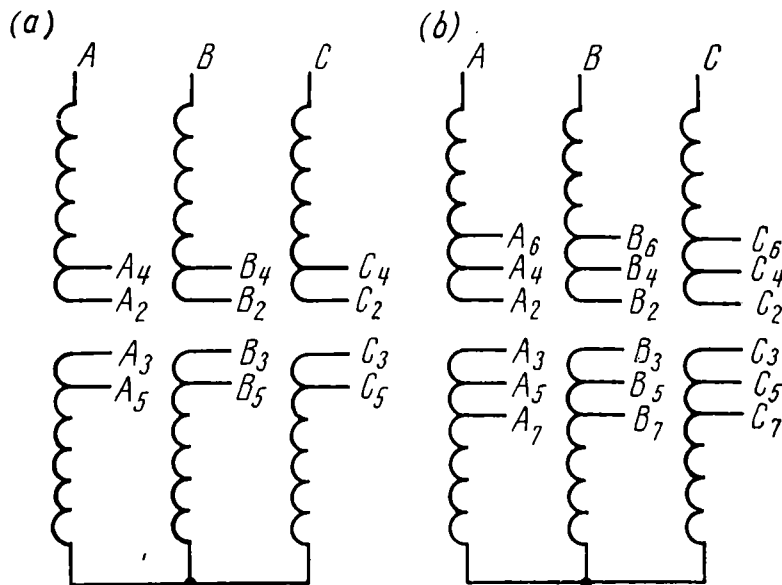


Fig. 9.1. Off-circuit tap changing. Centre-tapped winding (a) four taps per phase ($\pm 5\%$ regulation); (b) six taps per phase ($\pm 2 \times 2.5\%$ regulation)

Two basic schemes of the off-circuit tap changing can be used. The tappings in these schemes are changed by means of switches.

One such scheme (Fig. 9.1, *a*, *b*) is a centre-tapped winding (with a break in the middle of the winding). In this circuit one drum-type switch per phase is provided as shown

Table 9.2

Switch position	Voltage regulation step	Tap connection of phase <i>C</i>
I	+5%	C_2-C_3
II	+2.5%	C_3-C_4
III	Nominal	C_4-C_5
IV	-2.5%	C_5-C_6
V	-5%	C_6-C_7

in Fig. 14.21. Each of the three switches (in the three-phase transformer) has an individual drive mounted on the transformer tank cover.

Table 9.2 gives the sequence of connecting taps in accordance with voltage regulation steps (for phase *C* refer to Fig. 9.1*b*).

The connection of the taps of the remaining phases *A* and *B* is similar to that given above.

Another scheme (Fig. 9.2) is a near-neutral tapped winding

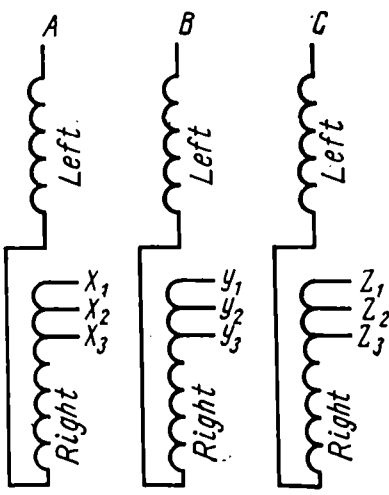


Fig. 9.2. Off-circuit tap changing. Near-neutral tapped winding ($\pm 5\%$ regulation)

having a single three-phase switch with nine contacts (see Fig. 14.24). The switch is connected to the neutral point of the star-connected windings and therefore this switch is referred to as a neutral switch. The sequence of tap changing is given in Table 9.3.

It should be pointed out that the current-carrying parts of the switch, being directly coupled with the winding, should be adequately insulated to withstand the given voltage.

Table 9.3

Switch position	Voltage regulation step	Connection
I	+5%	$X_1-Y_1-Z_1$
II	Nominal	$X_2-Y_2-Z_2$
III	-5%	$X_3-Y_3-Z_3$

Switch construction will be covered in greater detail in Ch. Fourteen.

During the off-circuit tap changing the transformer is completely de-energized to avoid arcing at the point of break in the switch circuit or shorting of a portion of the winding turns and thus to prevent failure of the transformer. Therefore, the energy supply has to be interrupted from time to time, which is highly undesirable.

9.3. On-Load Tap Changing. Equipment Used

The development of large power-supply systems with more convenient power control calls for an ever growing introduction of methods for on-load tap changing.

The on-load voltage regulating schemes have been long known. The USSR electrical engineering industry began to manufacture the on-load voltage regulating transformers back in 1935. In recent years such transformers have found particularly extensive application and henceforth almost all of the powerful transformers rated at 110 kV and above are manufactured with the on-load tap changing equipment.

As is evident from Table 9.1, the power transformers with on-load tap changers have a wider voltage adjustment range than the transformers with off-circuit tap changing, and hence more complicated connections of the voltage regulating windings.

The most popular is the scheme containing the built-in voltage regulator (Fig. 9.3a). In a simplified form this scheme comprises a power transformer with a voltage regulating winding, the tappings of which are changed over under load

by means of an on-load tap changing device, known as an on-load tap changer.

Reverse schemes employing special reversers are occasionally used to cut down in half the expenditure of materials which go for the manufacture of regulating windings. A scheme of this kind is illustrated in Fig. 9.3b. However,

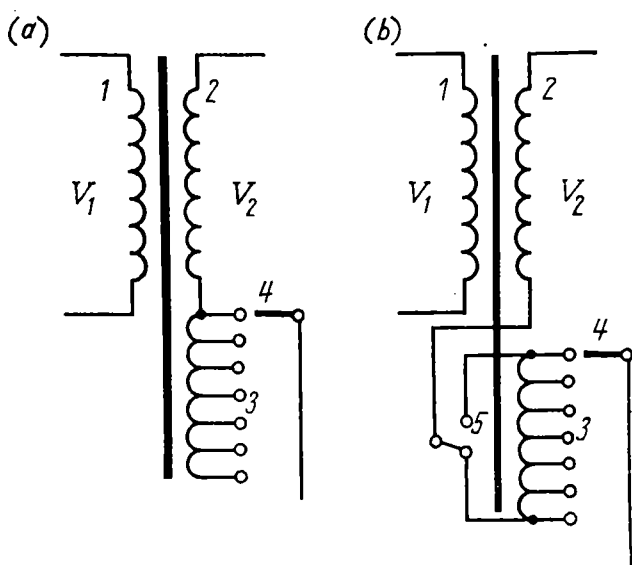


Fig. 9.3. On-load tap changing

(a) built-in voltage regulator circuit; (b) reverse scheme; 1—primary; 2—secondary; 3—tapped regulating winding; 4—tap changer; 5—reverser

these schemes involve the use of more complicated and more expensive tap changing equipment.

The on-load voltage regulating transformers are generally more bulky, have a greater weight, and, consequently, are more costly than the off-circuit voltage regulating transformers of the same kVA output and voltage class. The cost increase is most notable in the case of lower capacity transformers. Thus, the cost of a transformer rated at 1000 kVA output and 35 kV provided with an on-load tap changer is almost two and a half times the cost of an identical transformer with an off-circuit tap changer. The cost increment drops with an increase in the transformer power because the specific cost of the tap-changing gear decreases in respect to the cost of ferromagnetic and conducting materials.

Besides, the cost of the on-load voltage regulating transformer rises on account of a wider voltage regulation range which calls for a higher standard power.

The cost of the above transformer also depends on whether the voltage is changed on the side of a regulating or non-regulating winding, i.e., whether the transformer operates at an invariable value of inductance (if the taps are changed in accordance with the voltage applied) or a variable value (if the voltage is changed across the other, non-adjustable winding). In the latter case the expenditure of the materials per transformer is higher because this type of transformer has to be designed for the least value of inductance.

The added expenditure of the active components at a wide voltage regulation range and at an invariable value of inductance may be approximately determined by $0.5\ n\%$ for copper windings and $0.25\ n\%$ for electrical steel, where n is the percentage regulation range.

If the voltage is regulated on the side of the non-adjustable winding, i.e., with a change of inductance, the additional expenditure of the active components as compared with the foregoing case will be approximately three times as much, that is, $1.5\ n\%$ for copper and $0.75\ n\%$ for steel. The standard power of the transformer will be increased accordingly.

In the majority of cases the tap changers are connected across the neutral of the regulated winding, owing to which these devices have minimum insulation level as regards the voltage value.

In addition to the transformers with built-in voltage regulating devices, the adjustable autotransformers and the so-called step voltage regulators are also in use; the step voltage regulators usually consist of a regulating and a series transformer. However, the design and operation of these transformers are beyond the scope of this book and we refer the interested reader to the special literature on this subject (Ref. 7).

9.4. Tap Changer Design and Operation

The tap changers now in use are of varied designs. We shall consider only two basic schemes with current-limiting reactors or resistors,

Figure 9.4 shows a most common symmetrical tap-changing circuit with a reactor and displays a sequence of tap changing operations and intermediate tap positions. In the figure, S_1 and S_2 are the switches, K_1 and K_2 indicate the contactors and X is the reactor.

The scheme is based on the principle of a ganged switch and accomplishes the basic function of on-load tap changing.

The purpose of the contactors used in the reactor circuit is as follows. The change-over from one voltage step to another effected by each tapping switch must inevitably result in the interruption of current in a given branch and the subsequent arcing. The breaking capacity of large power transformers which is as high as 1000 kVA and even more per switch contact would bring about a severe burning of contacts. That is why the circuit break and tap changing functions have to be separated although this makes the entire equipment more expensive.

The arc is broken by contactors immersed in an individual tank. Thus the tap changing, i.e., the change from one voltage step to another is made by the de-energized switch whose contacts are not carbonized under these circumstances. The contacts immersed in an individual tank can be easily inspected and replaced without opening the transformer main tank and the oil spoiled by arcing can likewise be renewed with ease.

At a relatively small kVA rating (below 6300 kVA) the contactors may be dispensed with but then the switches should be so constructed as to afford tap changing in an energized state. The switchgear in this case should be immersed in an individual oil tank.

The switching operations in the reactor circuit are effected by alternately shifting the movable contacts of both switches S_1 and S_2 from one tap to another.

In the initial operating position both contactors K_1 and K_2 are closed and both switches are on the same tap. The primary current then branches out and flows through the switches, contactors and the halves of the reactor winding and leaves it through the centre tap of the reactor (Fig. 9.4a).

The sequence of changing from one tap (Fig. 9.4a) to another (Fig. 9.4g) is as follows. Contactor K_1 (Fig. 9.4b) breaks first and then de-energized switch S_1 is shifted to the

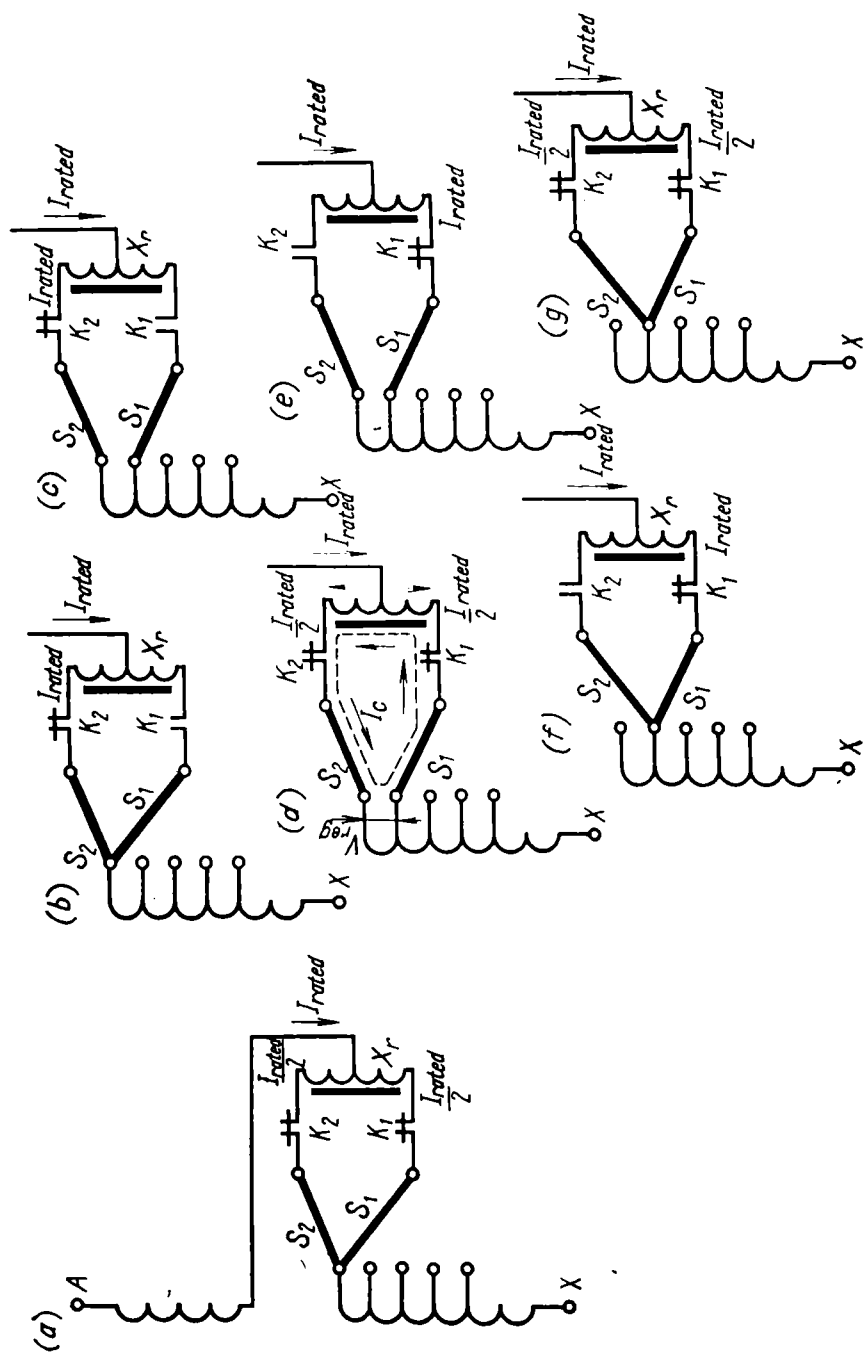


Fig. 9.4. Tap changing circuit diagram with symmetrically coupled reactor. Sequence of tap changing

lower tap (Fig. 9.4c). Now the working current flows through the upper half of the circuit via switch S_2 and contactor K_2 . Then contactor K_1 becomes closed, bridging the regulating portion of the winding (between the two taps) to the reactor (Fig. 9.4d). The working current is branched off through two parallel paths. Besides, a circulating current is produced in the closed loop thus formed, which is equal to

$$I_c = \frac{V_{reg}}{X}$$

where V_{reg} = regulating-step voltage

X = inductive reactance of the reactor

After the bridging state, contactor K_2 is broken and de-energized switch S_2 shifts to a lower tap. The tap changing is completed on closing contactor K_2 (Fig. 9.4 e, f, g).

The sequence of positions in tap changing is shown in Table 9.4.

Table 9.4

Contactors and switches	Positions						
	Up			Br			Low
K_1	0			0	0	0	0
K_2	0	0	0	0			0
S_1	Up	Up	Low	Low	Low	Low	Low
S_2	Up	Up	Up	Up	Up	Low	Low

Note. Up and Low mean upper and lower positions of switches S_1 and S_2 , Br, bridging connection and 0, contactor closed.

To change to the next tap, the entire sequence should be repeated.

In the three-phase transformer, the switchgear is so arranged that the switches and contactors bearing identical numbers, for example, S_1 and K_1 , operate in all the three phases at a time.

The switches and contactors are motor-driven through a gearing drive. The alternate action of each group of identical switches is effected by means of the Geneva drive while the contactors are operated by the cam mechanism. One

turn of the driving shaft effects one complete switching cycle, that is transition from one voltage step to another.

The Geneva drive consists of a driver and a driven wheel (Fig. 9.5). During a continuous and uniform rotation of the driving shaft which mounts the driver, the wheel seated on

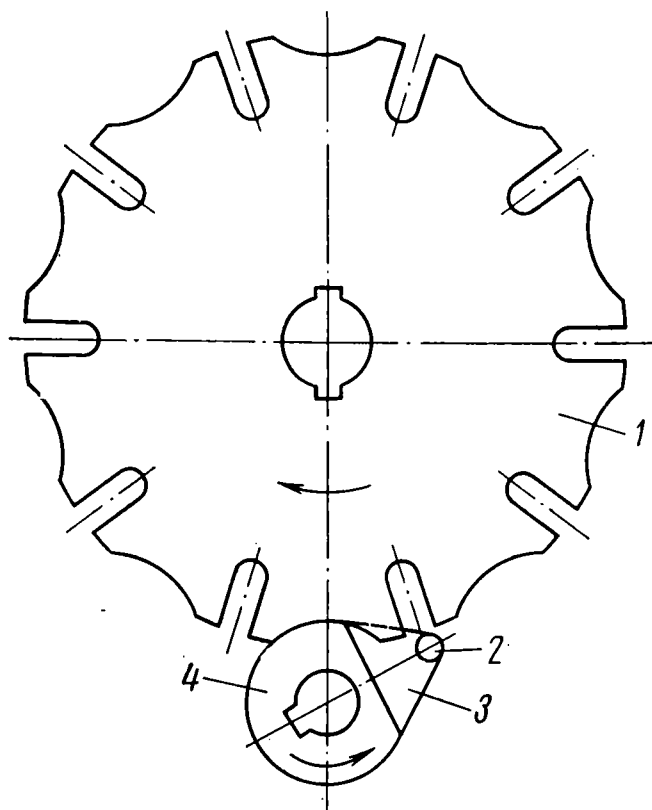


Fig. 9.5. Geneva drive

1—Geneva wheel; 2—tooth; 3—crank; 4—lock

the shaft of the tap-changer contact-assembly runs intermittently in accordance with the sequence of switch operations.

The contactors are driven by the cam mechanism (Fig. 9.6) which transforms the uniform rotation of the driving shaft into an intermittent motion. The appropriate positions of the driving cams and drivers interconnected through the medium of shafts, gears, and couplings provide for a desired sequence of contactor and switch movements.

Figure 9.7 shows the type PHT-13 tap-changer typical for the domestic on-load tap changing transformers. The external view of the type PHT-13 tap changer principal subu-

nits—the switch and the contactor—are demonstrated in Fig. 9.8.

The current-limiting reactors are usually designed for prolonged operation under load current and therefore the switchgears employing the reactors are suitable for a continuous duty at intermediate positions. The drives of the reactor switchgear do not require any fast-acting mechanisms and are fairly dependable in service.

Figure 9.9 shows one of the most popular tap-changing schemes with the symmetrically connected current-limiting

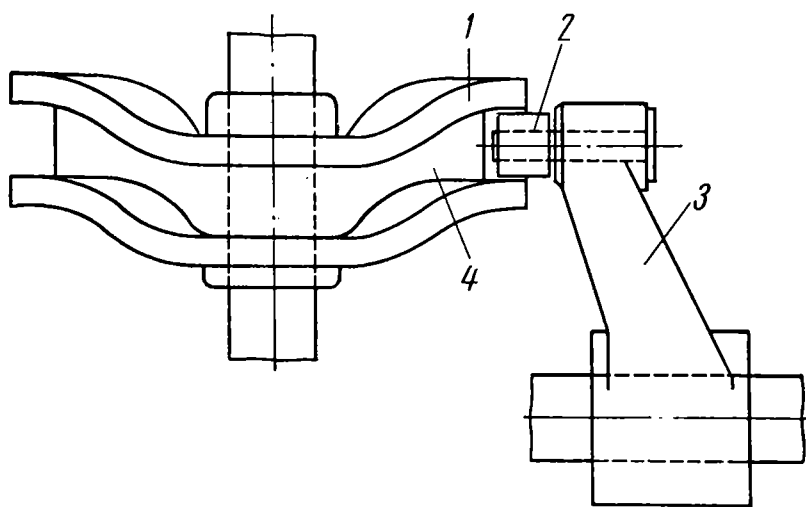


Fig. 9.6. Cam mechanism

1—cam; 2—roller; 3—crank; 4—guide groove

resistors. The diagrams illustrate intermediate positions of switch and contactor contacts when changing from one voltage step to another.

This scheme is also effective for the adjustment of the transformation ratio without interrupting the load current.

Suppose the transformer is operating on tap *I* (Fig. 9.9a) and it is desired to shift to tap *III* (Fig. 9.9f).

As is seen from Fig. 9.9a, initially the load current flows through a switch contact S_1 and a contactor contact K_1 . Here, in contrast with the reactor circuit, the de-energized contact of switch S_2 shifts first to the desired tap (Fig. 9.9b). Then, the following sequence of events occurs in the contact assembly: contact K_1 breaks (Fig. 9.9c) and contact K_3

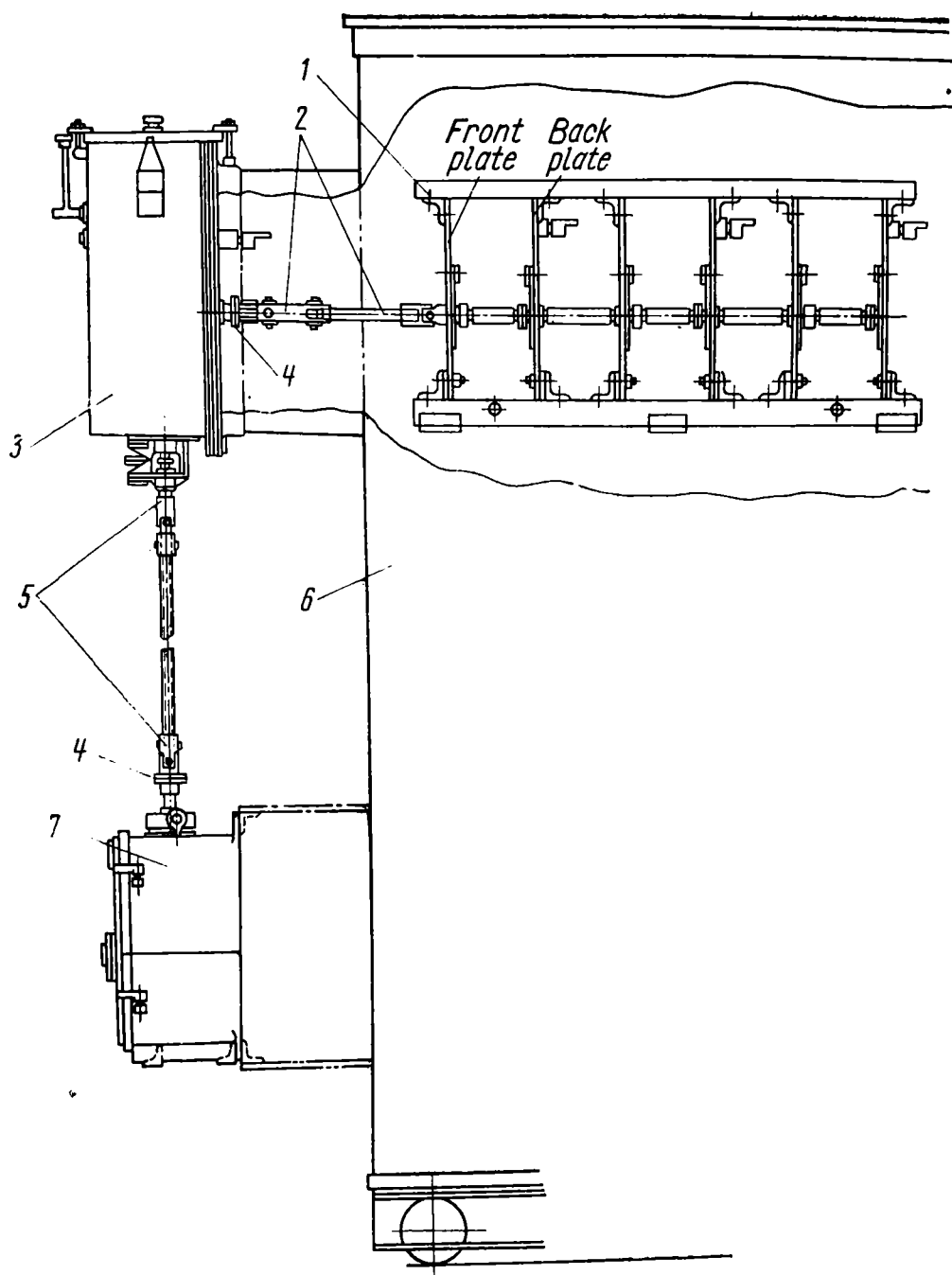


Fig. 9.7. Type PHT-13 tap-changer components
 1—switch; 2—horizontal shaft; 3—contactor box; 4—vernier coupling; 5—vertical shaft; 6—transformer tank; 7—drive gear box

makes, forming a bridge connection (Fig. 9.9*d*), contact K_2 opens (Fig. 9.9*e*) and finally contact K_4 makes (Fig. 9.9*f*). As is apparent from Fig. 9.9*d*, the short-circuit current through the bridged voltage-regulating tap is limited by

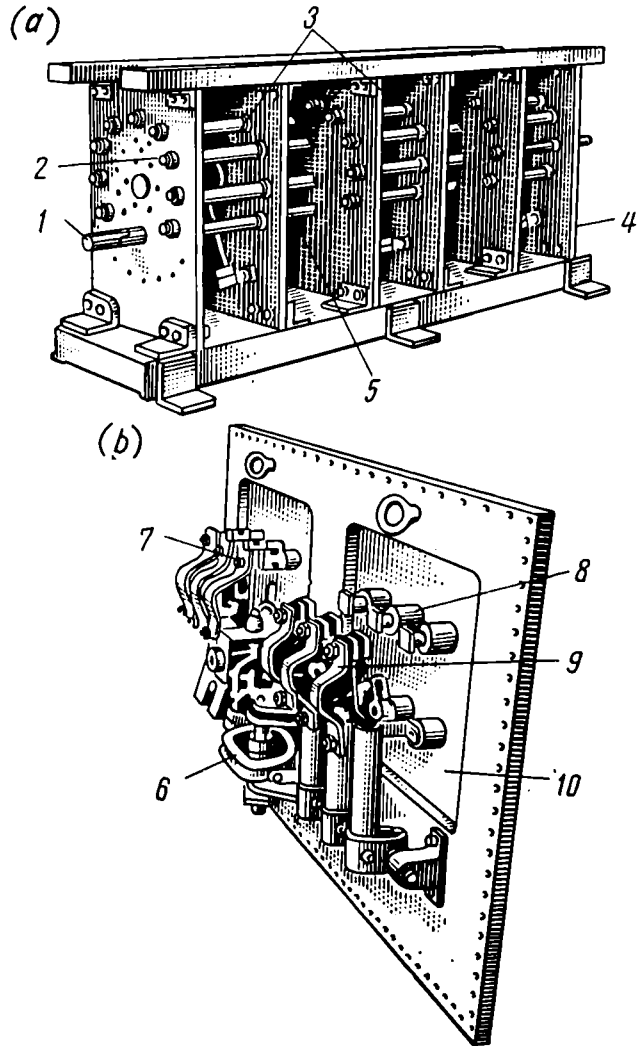


Fig. 9.8. Type PHT-13 on-load tap changer. Switch and contactor (a) switch; (b) contactor; 1—universal joint; 2—fixed switch contacts; 3—ganged switches; 4—frame; 5—shaft; 6—cam mechanism; 7—left-hand contact group of contactor; 8—fixed contacts of contactor; 9—right-hand contact group of contactor (open); 10—mounting plate

two series-connected resistors r_1 and r_2 which determine the circulating current I_c .

Contacts K_1 and K_2 are used to break the arc at full load current (K_1) and at half the load current (K_2).

The tap changers with current-limiting resistors find an extensive application because they possess the following advantages over the reactor circuits.

1. The current-limiting resistors are much smaller than the reactors and as such may be embodied into the contactor, constituting the inherent part of the contactor, whilst the reactors have to be housed in a tank and their windings must

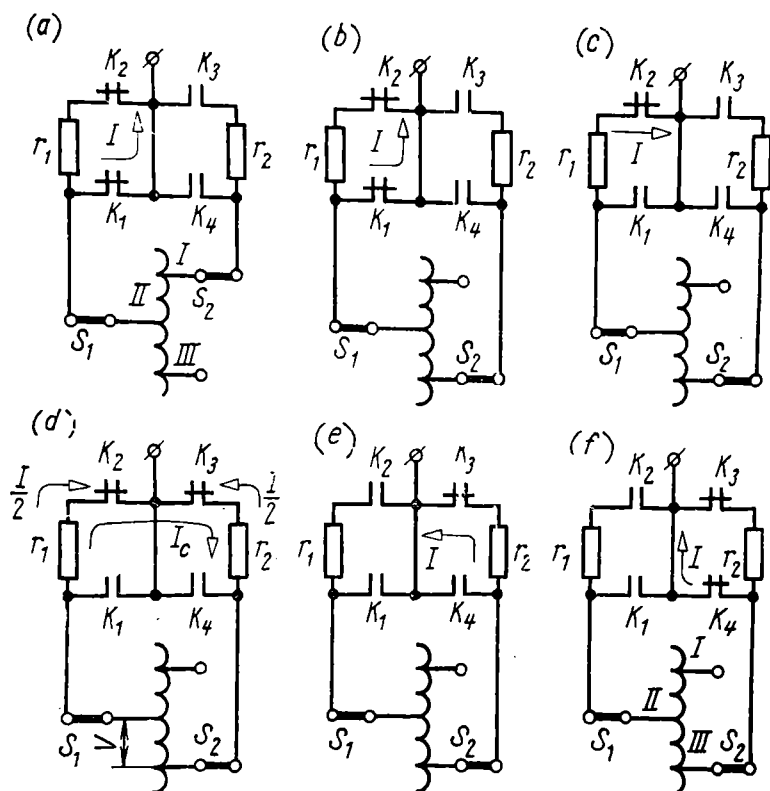


Fig. 9.9. Tap changing circuit diagram with symmetrically coupled resistor. Sequence of tap changing

be insulated to withstand the full working voltage of the regulating winding.

2. The devices using these resistors do not need individual tanks for contactors because the arc extinction here is very fast (occurring in fractions of a second).

However, the tap-changing devices with current-limiting resistors are, as a rule, more complicated as compared to those incorporating reactor circuits. The resistors are designed only for a short-time duty while the use of powerful springs, fast speed of moving parts and resultant mechanical shocks impose stringent requirements for the ruggedness of

the construction, quality of materials and precision in the manufacture of switchgear.

Nevertheless, the above-mentioned advantages of the resistor-type tap changing devices and mainly their smaller size, compelled European and American manufacturers and those in the USSR to give preference to exactly this type of tap changing equipment. This is directly associated with the development of super-powerful HV autotransformers.

9.5. Determination of Resistances of Current-Limiting Reactors and Resistors

As has been mentioned above, the current-limiting reactor is needed in the bridge transition, i.e., when switches S_1 and S_2 are connected with different winding taps (see Fig. 9.4c). The winding section between these two taps should be guarded against overheating and therefore the current flowing through this section, which is the sum of the circulating current I_c and half the rated current, should not exceed the rated current I_{rated} :

$$I_c + \frac{I_{rated}}{2} \leq I_{rated} \text{ or } I_c \leq \frac{I_{rated}}{2}$$

The circulating current is determined by the voltage V_{reg} of a regulating step of the winding and inductive reactance X of the reactor:

$$I_c = \frac{V_{reg}}{X}$$

Hence,

$$\frac{V_{reg}}{X} \leq \frac{I_{rated}}{2} \text{ or } X \geq \frac{2V_{reg}}{I_{rated}}$$

Thus, the inductive reactance X should not be less than the doubled regulated voltage at the regulating step divided by the rated current. In this case the resistances of the switches and contactors are neglected. The reactor winding is commonly designed for a continuous-running duty at a rated current.

Similarly, we can determine the resistance values of the current-limiting resistors

$$R = \frac{V_{reg}}{I_c}$$

where the circulating current is chosen to be equal to the load current I_{rated} .

Since the voltage steps in the resistor-type switchgear are selected by means of the fast-action devices and the circuitry of the switching apparatus is so arranged that there is no interruption in the bridge position, high current density is allowed in the resistors and, consequently, the size of these resistors is made small.

9.6. On-Load Stepless Voltage Regulators

If the transformer rating does not exceed a few dozen kVA, its voltage may be regulated steplessly. Of the various stepless voltage-regulation schemes we shall discuss only two now in use in the USSR transformer industry.

Transformer with movable contacts. In these transformers a movable contact (carbon brush or roller) rides over the bare turns of the regulating winding.

The diagram showing this kind of voltage-regulating transformer with movable contacts is shown in Fig. 9.10a.

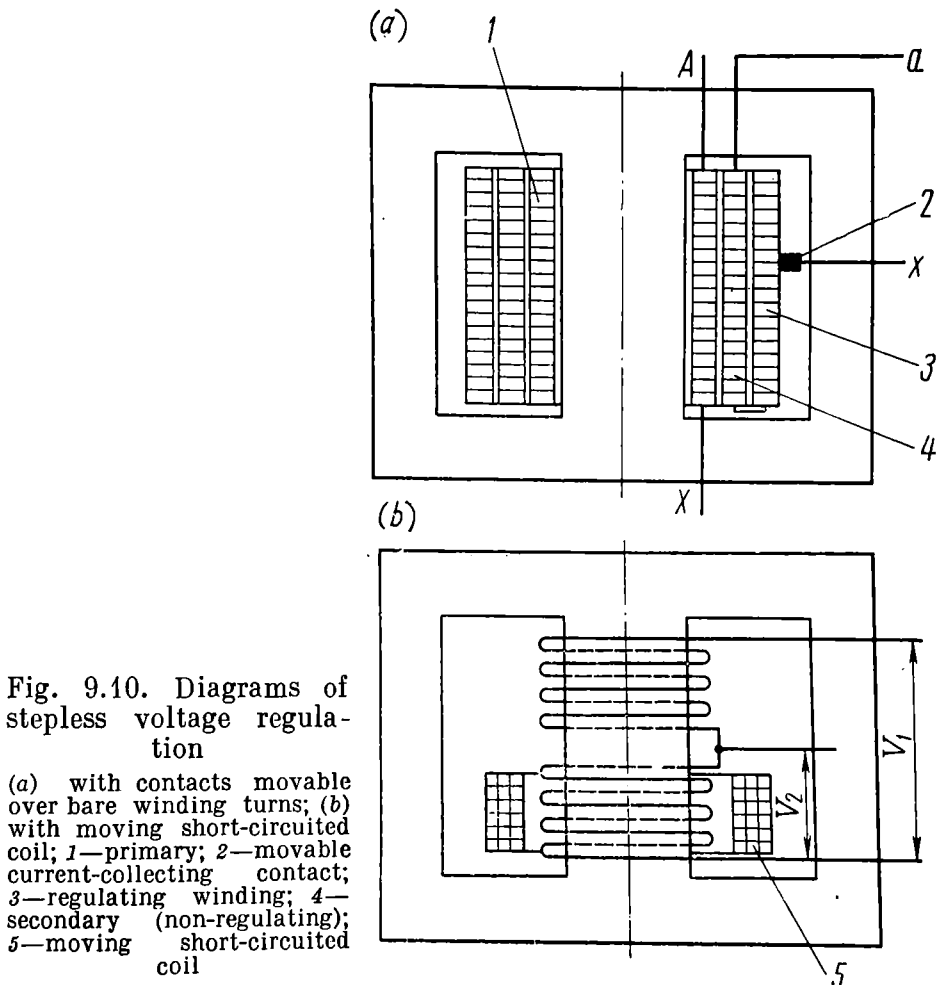
The arrangement provides for a small-stepped voltage regulation of the transformer. To prevent the interruption of current during the brush movement, the brush overlaps two or three turns of the winding. The carbon brush composed of graphite of a specially-chosen grade, behaves as the current-limiting resistance. To avoid arcing and overheating, the voltage per turn is limited to 1 V and the power on contact to 40 VA. In the case of large currents two and more parallel-connected brushes are used.

The transformers with movable contacts are often used for voltage regulation and their design is made on the basis of the autotransformer principle. The voltage-regulating transformers with windings wound around the toroidal cores and fitted with roller commutators are manufactured for laboratory uses and household appliances.

The disadvantages of these transformers are the wear of brushes and cumbersome construction involving the use of moving parts and assemblies.

Transformers with moving coils. The transformer has a shell-type magnetic circuit with elongated legs and side yokes. In the most simple form, the leg carries two windings,

the turns of which are wound in opposition as shown in Fig. 9.10*b*. A short-circuited coil placed over the two windings is free to move up and down the leg. The moving coil is of the same height as that of the main coils, i.e., it is



somewhat shorter than half the window height of the magnetic core.

This transformer behaviour is based on Lenz's law according to which the sum of the fluxes inside the short-circuited loop (the third coil in our case) is zero. Therefore, when the moving coil is shifted to the top of the leg, all the primary voltage becomes as if impressed only on the lower coil and the secondary voltage will be equal to the primary voltage. When the moving coil is shifted towards the bottom

of the leg, the secondary voltage smoothly decreases because the flux is gradually forced out of the lower coil. And, eventually, in the extreme bottom position, the secondary voltage will be nearly zero.

Thus, the voltage can be continuously varied approximately over a range from 0 to V_1 by varying the position of the moving coil.

Depending on the transformer uses, more intricate circuits may be developed according to the same moving-coil principle. For example, a three-phase transformer may be manufactured as a bank of three single-phase transformers with the associated moving coils displaced by means of a motor drive. These transformers are often used as the supply voltage regulators equipped with adequate automatic devices.

The limitations of the moving-coil voltage regulating transformers are the increased values of open-circuit currents and reactance drops, the complicated construction which includes moving parts, and large dimensions because their flux density is half that of the ordinary transformers.

Review Questions

1. What is the purpose of voltage regulation in power transformers?
2. Which of the off-circuit tap-changing schemes do you know?
3. What is the basic shortcoming of the off-circuit tap changing schemes?
4. Explain the principle of operation of the ganged switch in use with the on-load tap changers.
5. What is the purpose of current-limiting reactors and resistors in the on-load voltage regulating circuits?
6. Why are the contactors immersed in an individual oil tank?
7. What is the function of a short-circuited coil in the moving-coil regulators?

Chapter Ten

Thermal Properties and Heat Effects

10.1. Effects of Heat on Transformer Materials

All the losses occurring in the magnetic core, windings and parts of an operating transformer are converted into heat.

The transformer materials, notably insulating materials, withstand but certain maximum temperatures. An allowable heat limit for each material is established experimentally on the basis of a reliable and long service of the transformer. For all that, a more effective utilization of the transformer active components often leads to their excessive heating. Therefore, when calculating and designing a transformer it is important to choose a satisfactory method of its cooling in service.

The heat developed in the transformer is dissipated into the surrounding medium. This heat is conducted through transformer outer surfaces, i.e., the windings and core of the dry-type transformer and through the tank walls and cooling devices of the oil-immersed transformers. But for the heat flow, the transformer temperature would rise continuously because of the transformer heat capacity which would deteriorate its insulation (that suffers most from overheating) and soon make the transformer unserviceable.

The transformer kept in the de-energized state for some time has a temperature of the surrounding air. Heating begins as soon as the transformer is started. When the temperature of the transformer parts becomes higher than the ambient temperature, the heat is transmitted to the surrounding medium. At this instant the transformer cooling begins. But once the transformer starts transferring heat to the

surrounding air, a further rise of its temperature will be slowed down by the increased cooling until, eventually, a steady working temperature is reached. At this steady thermal state the amount of heat produced will be equal to the amount of heat carried away from the transformer, owing to which the temperature rise of the transformer over the ambient will become constant. For brevity, the temperature rise is often called overheating.

Any hot body is cooled by dissipation of heat from its surface. The heat is dissipated by (a) radiation of heat, and (b) by convection (transmission of heat by movement of the heated particles of air). Such cooling is implemented in a dry-type transformer.

However, the air cooling is not so effective and proves insufficient even for transformers of medium sizes. The oil cooling which was introduced back in 1889 is more effective and allows the use of large-size transformers with high voltage ratings.

Thus the transformer temperature is the sum of the temperature rise and the ambient air temperature. However, the temperature rise depends on the transformer losses which in turn depend upon the transformer load, i.e., upon its design and service conditions, and is practically independent of the ambient air temperature. Therefore, calculation of transformer thermal properties is reduced to the determination of overheating of its parts rather than of their temperature because the transformer temperature will vary with a change in the air temperature.

In view of the fact that the transformer heating is limited to a definite temperature, the maximum permissible overheating is determined with respect to the highest possible ambient temperature which is taken as $+40$ degrees centigrade for most parts of the Soviet Union in the conditions of seasonal and daily temperature variations.

10.2. Overheating Limits and Temperature Measurement

The permissible overheating limits for the individual parts of oil-immersed power transformers specified by the appropriate standards are listed in Table 10.1.

Table 10.1

Transformer parts	Temperature rise, °C	Measurement technique
Windings	65	By resistance change
Surfaces of cores and structural components	75	Thermometer
Upper oil layers: transformers of (a) enclosed design or those provided with devices fully isolating oil from surrounding medium	60	Thermometer
(b) open designs	55	Thermometer

The overheating limits for windings given in Table 10.1 are established with respect to maximum permissible temperatures of 105° to 110°C which are chosen on the basis of the class of insulation and also the evidence of research and service experience ($65 + 40 = 105^{\circ}\text{C}$).

However, the average temperature of the winding within the total service life of the transformer will be much below 105°C because of the ambient temperature fluctuations and variations in load. The estimated (reference) temperature of the windings, defined by the standards, to which the losses and impedance voltage of the oil-immersed transformers should be referred, is chosen at +75°C. Under these conditions the service life of the transformer insulation is estimated at 15 to 20 years.

Since a direct measurement of the winding temperature is impossible because the winding is inaccessible and live, its temperature is determined by utilizing the well-known property of metallic conductors to change their electrical resistance with temperature. The resistance-temperature relationship of the winding is expressed by the following empirical formula (true for a temperature range up to 150°C):

$$\frac{R_2}{R_1} = \frac{235 + \theta_2}{235 + \theta_1}$$

where R_1 and R_2 are resistances of the winding (copper or aluminium conductors) measured respectively at temperatures θ_1 and θ_2 .

This method is good only for the determination of the average temperature because the heat is distributed nonuniformly over the winding height (Fig. 10.1). The hottest-spot part of the winding is at a level of $2/3$ or $3/4$ of its height. Its temperature exceeds the average temperature of the winding by 10 to 15°C .

The oil temperature is determined directly by measuring the temperature of the upper oil layers with a thermometer

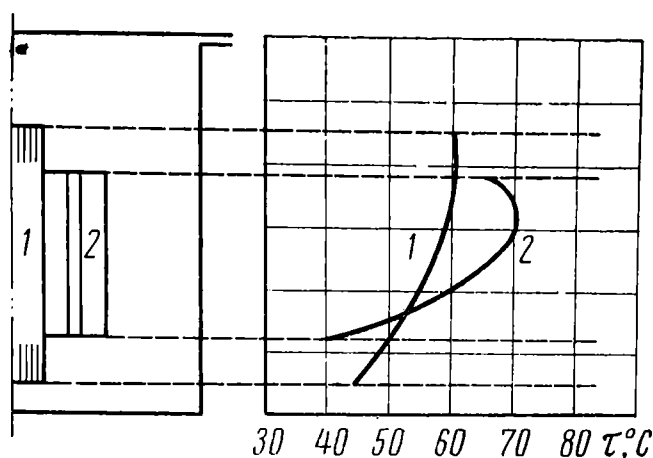


Fig. 10.1. Temperature rise through the height of transformer
1—core; 2—winding

in the case of low and medium-capacity transformers and with temperature detectors in the case of large-size transformers (see Fig. 14.12). The core temperature is measured with a thermometer or thermocouple. Usually, these measurements are made during acceptance or prototype tests.

To determine the temperature rise above the ambient temperature, the latter must be subtracted from the temperature of the winding or oil measured by the above-stated method. The air temperature is measured with a thermometer at a distance of 1.5 to 2 m away from the transformer. The thermometer is immersed in a vessel of oil to avoid errors in the thermometer reading due to movement of air around the transformer.

10.3. Heat Flow

The heat generated in the windings and the magnetic core of a transformer is transferred into the air in several stages due to a temperature difference at the boundaries of each stage.

The 1st stage of heat transfer begins from the interior of the winding or the core and extends to their external surfaces immersed in oil. At this stage the heat is transferred by way of heat conduction. If the winding were a homogeneous body uniformly cooled at each point with oil, i.e., if the winding were ideal from the point of view of its cooling, the heat distribution across its width (in the radial direction) would be proportional to the temperature gradient of the radial heat flow, i.e., follow the quadratic parabola law (Fig. 10.2). However, the temperature gradient in the actual winding is other than that in the ideal winding.

Therefore, the calculation of the internal temperature differences in the multi-layer winding is based on either empirical formulae or corrections to the estimated (reference)

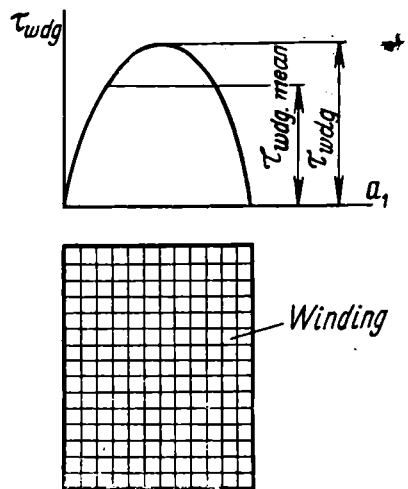


Fig. 10.2. Temperature rise across the winding section

temperature, which are found from experiments.

The thermal calculation of the power transformers is somewhat simplified due to the fact that each conductor of a layer winding or a continuous winding is immersed in oil so that no temperature difference practically exists inside the winding. Correction for the heat effect is introduced only when the added insulation of the winding turns and that of the coils are provided for.

The 2nd stage is the transfer of heat from the winding to oil. The temperature difference between the winding surface and the oil flowing over it depends upon the amount of heat emitted from the winding surface, location of the oil-cooled portions of the winding, size of the oil cooling ducts, and viscosity of the oil. The temperature difference (overheating) τ_{wdg} between the winding surface and the oil is determined by the formulae derived on the basis of experimental data for each type of winding. The temperature rise of the winding over the oil temperature is a function

of the specific heat load of the winding surface and may be expressed in the general form as

$$\tau_{wdg} = K_t q_{wdg}^n$$

where $K_t = \text{constant}$

q_{wdg} = specific heat load (density of the heat flow) of the winding surface, W/m^2

$n = 0.6 \text{ to } 0.7$ is the exponent determined experimentally as is the constant K_t

The appropriate equations for each type of winding are presented in Sec. 10.4.

The 3rd stage is the transfer of heat by the heated oil from the winding to the tank walls and the cooling devices. The oil passing over the transformer windings carries the heat produced in the winding from its surface. The heat is dissipated by convection, i.e., due to the motion of oil particles brought about by the difference in density of the hot and cold oil. The flow of oil around the winding will differ with the type of winding and also the shape, size and disposition of the oil ducts.

The oil heated at the surface of the winding comes to the upper part of the transformer tank, reaches the tank walls, gives up the heat carried away from the winding, then moves down to the bottom of the tank and thus returns to the winding. If the tank walls are provided with cooling tubes or external radiators, the heated oil enters the tubing or the upper pipe connection of the radiator, cools in the tubing surrounded by the ambient air, goes down into the lower part of the transformer tank and again flows to the windings. Then oil becomes heated again and rises carrying away the heat generated in the winding and the core. Thus a closed convection flow of oil is set up in the operating transformer and the oil circulates continuously (Fig. 10.3).

The 4th stage is the transfer of heat from the oil to the tank walls of the transformer when there is a temperature difference between the oil and the tank walls. This temperature difference is governed by the same laws as that between the winding and the oil, i.e., it depends on the specific heat load of the tank walls and the cooling devices.

The 5th stage is the transmission of heat energy through the thickness of the tank walls. The temperature difference

at this stage is not more than 1°C and therefore is usually neglected.

The 6th (and the last) stage is the dissipation of heat from the tank walls and the cooling devices into the surrounding air by natural air convection and heat radiation. Heat radiation is dependent on the temperature of the radiating body, the air temperature, the geometry of the tank walls and the cooling devices and also the conditions of their surfaces. The heat radiation from the smooth tank walls

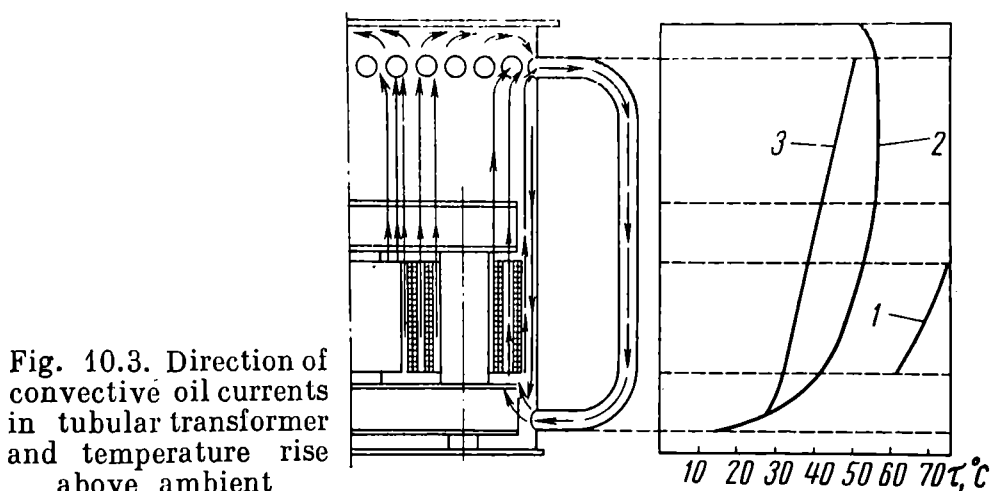


Fig. 10.3. Direction of convective oil currents in tubular transformer and temperature rise above ambient

coated with paints containing metal-free fillers reaches 50 to 55 per cent of the total heat dissipation. This percentage drops to 15 in the case of tubular tanks and the tank provided with radiators, which is accounted for by the rectilinear propagation of radiant energy. The heat energy is radiated here not from the entire surface but only from the external surface of the cooling device (Fig. 10.4).

Unlike the heat radiation, the dissipation of heat through convection occurs from the entire surface of the tank, tubes, and cooling devices, and depends on the temperature difference between the tanks walls and the surrounding air, height of the tank and its shape as well as the barometric pressure. Heat dissipation increases with an increase of the surface area of the tank and that of cooling devices, rise of the temperature of the walls and better access of the surrounding air to the tank walls.

When making practical thermal calculations, two fundamental temperature rises should be determined: the rise of the winding temperature over the oil temperature and the rise of the oil temperature over the ambient temperature, or, otherwise speaking, the difference between the temperatures of the winding and the oil, and between the oil and the

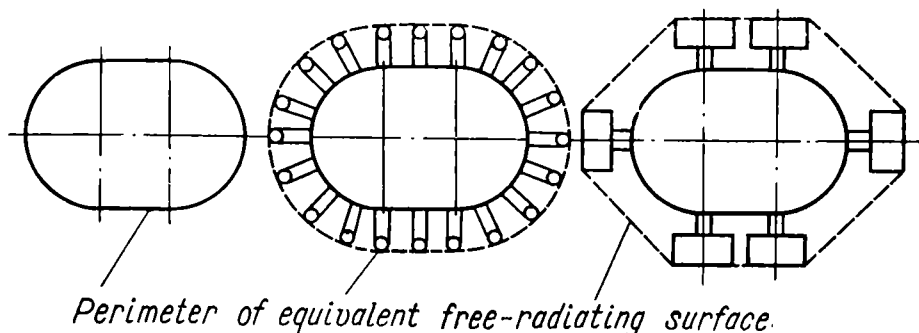


Fig. 10.4. Determination of equivalent heat radiating surface for smooth and tubular tanks and tanks with coolers

air. The sum of these two temperature differences will give a rise of the winding temperature above the air temperature. If required, the rise of the winding temperature over the oil temperature is corrected for the thermal conductivity of the added turn-and-interlayer insulation and the size of the oil ducts, and the oil temperature rise over the air temperature rise is corrected for the ratio of the height of the centre of losses in the active components to the height of the centre of cooling.

10.4. Calculation of Steady Rise of Winding Temperature Over Oil Temperature

Calculation of the winding overheating is based on the determination of its average value. This calculation method is convenient because the results may be verified experimentally as the average temperature (and therefore the overheating) may be measured by the change in the winding resistance. Hence, the standards for winding heating established on the basis of practical temperature measurement methods specify precisely the average temperature of the windings although the heating of the winding insulation is

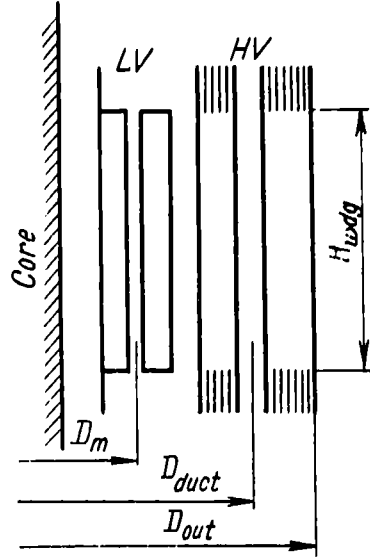
specified by the highest allowable temperature of the windings.

The steady temperature rise of the winding over the oil temperature is reached in about 20 to 30 minutes after the connection (or changing) of the load. All the heat generated in the winding is thereafter transferred to the surrounding oil.

Cylindrical layer windings. The mean temperature rise of the cylindrical windings over the oil temperature is

$$\tau_{wdg} = 0.159 q_{wdg}^{0.7}, \text{ } ^\circ\text{C} \quad (10.1)$$

Fig. 10.5. Sectional view of layer windings



where $q_{wdg} = P_{cu}/A_{cool}$ is the specific heat load, W/m^2

P_{cu} = copper losses, W

A_{cool} = cooled (heat-liberating) winding surface, m^2 ,
determined from the following equations
(refer to the nomenclature in Fig. 10.5):

(a) for the two-layer LV windings made of rectangular conductor

$$A_{wdg} = 3 \times 3.5\pi D_m H_{wdg} - 3 \times 3cn H_{wdg}, \text{ } \text{m}^2 \quad (10.2)$$

where D_m = the winding medium diameter, m

H_{wdg} = winding height, m

c = width of the batten between layers, m

n = number of battens around the circumference

(b) for the multi-layer HV windings made of round conductor

$$A_{wdg} = 3\pi D_{out} H_{wdg} + 3 \times 2\pi D_{duct} H_{wdg} - 3 \times 2cn H_{wdg}, \text{ } \text{m}^2 \quad (10.3)$$

where D_{out} = outer diameter, m

D_{duct} = diameter of the duct, m

The last terms in the equations for A_{wdg} allow for the covering of the cooling surface with battens.

For the transformers of 40 kVA and more, a duct is provided inside the HV winding spaced at a distance of one third of the winding thickness from its outer cylindrical surface (i.e., in its hottest spot). In the absence of the duct, only the outer surface defined by the first term of the equation (10.3) will be cooled.

A correction for the total thickness of the internal insulation (at $t > 2.5$ mm) should be added to the temperature rise of the multi-layer winding, obtained from equation (10.3):

$$\Delta\tau_{wdg} = 1.15(t - 2.5)q_{wdg} \times 10^{-3}, \text{ }^{\circ}\text{C}$$

where t = total radial thickness of the turn-and-interlayer insulation, mm

Disc, continuous and helical windings. The temperature rise of the disc windings over the oil temperature is the following:

For the inner windings

$$\tau_{wdg} = 0.41q_{wdg}^{0.6}, \text{ }^{\circ}\text{C} \quad (10.4)$$

For the outer windings

$$\tau_{wdg} = 0.358q_{wdg}^{0.6}, \text{ }^{\circ}\text{C} \quad (10.5)$$

The inner winding, as to its arrangement on the core, has the worst cooling conditions because of the more difficult circulation of oil in the cooling ducts.

The specific heat load of one coil (for the disc and continuous windings) or one turn (for the helical winding) is

$$q_{wdg} = \frac{21.4IN\delta K_{\Phi}K_c}{p} V/m^2 \quad (10.6)$$

where 21.4 = copper resistivity coefficient referred to 75°C

I = current through the winding turn, A

N = number of turns in coil

δ = current density, A/mm²

K_{Φ} = extra loss factor

K_c = factor of covering the coil surface

p = core cross section perimeter, mm

The factor K_c takes into account the covering of the coil surface by insulating parts (battens, spacers) which obstruct

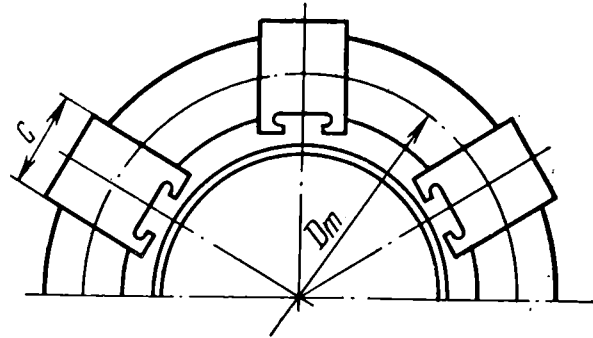


Fig. 10.6. Determining the coil-covering factor

the flow of oil. The factor K_c (the related nomenclature is shown in Fig. 10.6) is

$$K_c = \frac{\pi D_m}{\pi D_m - cn} \quad (10.7)$$

where D_m = medium diameter of coils, mm

c = spacer width, mm

n = number of battens (spacers) placed around the circumference

Table 10.2

Coil radial size, mm	K_{duct} against width (height) of oil duct, mm					
	4	5	6	7.5	8	10
20	-2.6	-3.7	-4.5	-5.2	-5.2	-5.2
22	-2.4	-3.3	-4.2	-4.9	-5.2	-5.2
24	-2.1	-3.0	-3.9	-4.8	-4.9	-5.2
26	-1.9	-2.7	-3.6	-4.6	-4.8	-5.2
28	-1.6	-2.4	-3.3	-4.4	-4.6	-5.2
30	-1.4	-2.2	-3.1	-4.2	-4.4	-5.2
32	-1.2	-2.0	-2.8	-4.0	-4.2	-5.0
34	-1.0	-1.8	-2.6	-3.7	-4.1	-4.9
36	-0.7	-1.6	-2.3	-3.5	-3.9	-4.8
38	-0.4	-1.4	-2.2	-3.3	-3.7	-4.6
40	-0.1	-1.2	-2.1	-3.1	-3.5	-4.5
45	*	-0.7	-1.6	-2.7	-3.0	-4.2
50	*	-0.2	-1.2	-2.3	-2.6	-3.9
55	*	+0.1	-0.8	-2.0	-2.3	-3.5
60	*	+0.4	-0.3	-1.7	-2.0	-3.2
65	*	*	0	-1.3	-1.7	-2.9
70	*	*	*	-1.0	-1.4	-2.6

* Inapplicable relationships of the oil duct sizes.
 Note. If the coil radial size has intermediate values, take the nearest larger value (in the positive direction) of factor K_{duct} .

The spacer width c is usually taken at 40 mm. The number of battens is chosen so as to obtain the covering factor K_c equal to 1.2 to 1.4.

The temperature rise of the disc winding determined by Eq. (10.4) or (10.5) is corrected for the added thickness, if any, of the insulation, $\Delta\tau_{wdg1}$ and for the effect of the width (height) and depth of the oil duct between the coils (turns) on the convection of oil, $\Delta\tau_{wdg2}$,

$$\Delta\tau_{wdg1} = 3.1(t - 0.5)q_{wdg} \times 10^{-3}, \text{ } ^\circ\text{C} \quad (10.8)$$

where t = doubled thickness of the turn insulation, mm.

$$\Delta\tau_{wdg2} = K_{duct}q_{wdg} \times 10^{-3}, \text{ } ^\circ\text{C} \quad (10.9)$$

where K_{duct} = factor chosen from Table 10.2, which depends upon the size of the oil cooling duct.

10.5. Calculation of Steady Rise of Oil Temperature Over the Ambient

The overheating of oil is calculated also on the basis of its average temperature rise.

The average temperature rise of oil, τ_{oil} , i.e., the average oil overheating through the height of the tank (Fig. 10.7)

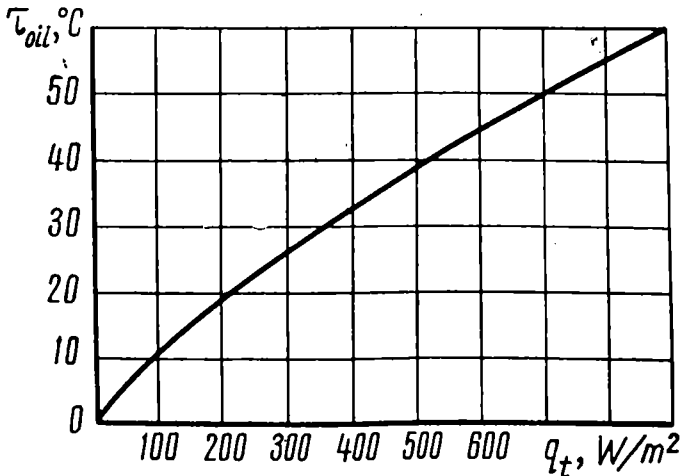


Fig. 10.7. Curve showing average temperature rise of oil above ambient versus specific heat load of natural-cooled tank

is determined for the case of natural cooling by the curve shown in Fig. 10.7. The equation which yields this curve is

$$\tau_{oil} = 0.262q_t^{0.8}, \text{ } ^\circ\text{C} \quad (10.10)$$

where $q_t = \frac{P_0 + P_{sc}}{A_t}$ = specific heat load of the tank surface (or cooling device,) W/m^2

A_t = cooled (heat-liberating) surface of the tank and cooling device reduced to a smooth tank wall, m^2

The highest oil temperature rise is in the upper layers of oil where the oil temperature is measured. The overheating value of the upper oil layers, $\tau_{u.o}$, which should not be greater than the values listed in Table 10.1 is determined from the empirical formula

$$\tau_{u.o} = 1.2\tau_{oil} + \Delta\tau_{oil} \quad (10.11)$$

where $\Delta\tau_{oil}$ = correction for the ratio

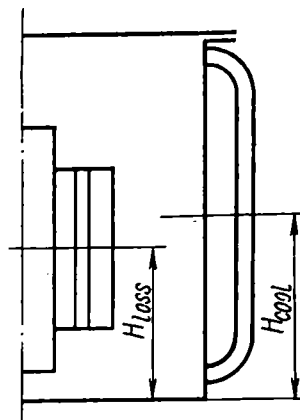


Fig. 10.8. Heights of the centres of losses (H_{loss}) and cooling (H_{cool}) of oil-filled transformer

of the centre of losses to the centre of cooling (H_{loss}/H_{cool}) taken from Table 10.3.

Figure 10.8 illustrates the data contained in Table 10.3.

Table 10.3

H_{loss}/H_{cool}	Correction $\Delta\tau_{oil}$, °C, as a function of temperature rise in upper oil layers				
	40	45	50	55	60
0.5	2.4	2.5	2.6	2.7	2.8
0.55	2.6	2.7	2.8	3.0	3.2
0.6	2.8	2.9	3.1	3.4	3.6
0.65	3.1	3.3	3.5	3.8	4.0
0.7	3.5	3.7	4.0	4.5	4.9
0.75	4.0	4.5	4.9	5.4	6.0
0.8	5.0	5.4	5.8	6.5	7.5
0.85	5.8	6.3	7.4	8.4	9.5
0.9	7.1	8.1	9.0	10.0	11.0
0.95	9.0	9.9	10.8	12.0	13.0
1.0	10.5	11.5	12.7	14.0	15.0

Note. The temperature rise of the upper oil layers is assumed to be equal to $1.2\tau_{oil}$.

As is seen from the Table, the smaller the relationship between the heights of the centres of losses and cooling, the smaller the correction for oil overheating. This is attributed to a greater rate of oil circulation.

10.6. Cooling of Oil-Immersed Transformers. Determination of Tank Size and Surface Area

The oil-immersed transformers rated up to 40 kVA may have only smooth tank walls without additional cooling facilities.

To keep the temperature rise of the upper layers of oil within permissible 55°C , the specific heat load of the tank, q_t , according to the above-given equations (10.10) and (10.11), should not exceed 570 to 580 W/m^2 . It is precisely this value of q_t that is reached for the transformers of up to 40 kVA, when relating the total transformer losses to the losses of the tank walls.

For the transformers of larger capacity the smooth tank surface is already insufficient to dissipate heat and therefore has to be artificially increased. This is explained by the fact that the transformer losses rise in proportion to the weight of copper and steel and therefore to their volume, i.e., the cube of the transformer linear dimensions, whilst the surface area of the tank increases only as the square of its linear dimensions. In other words, with the increase of transformer power, the increase of the transformer cooling surface lags behind the rise in its power losses. Hence, to prevent a further rise in oil temperature with the growth of transformer power, it is necessary to employ additional cooling devices.

In the transformers of up to 1600 kVA, the surface area of the tanks is increased by using the external tubes welded to the main tank in one, two, three or, occasionally, four rows, depending on the transformer power. A further increase in the number of tube rows proves low-effective and therefore the transformers of over 1000 to 1600 kVA and up to 10,000 kVA use smooth tanks with tubular radiators of a single or a double type. They are connected to the main tank through the flanged pipe connections welded into the tank.

At a power above 10,000 kVA, the natural oil cooling becomes insufficient in spite of the use of external coolers and therefore air-blast cooling (when the coolers are cooled by a blower), forced-oil cooling, etc., are employed.

To determine the heat-dissipating surface of a tank, it is necessary to know its minimum dimensions.

The tank of the three-phase power transformer is usually of an oval shape in plan. Such a shape of the tank follows

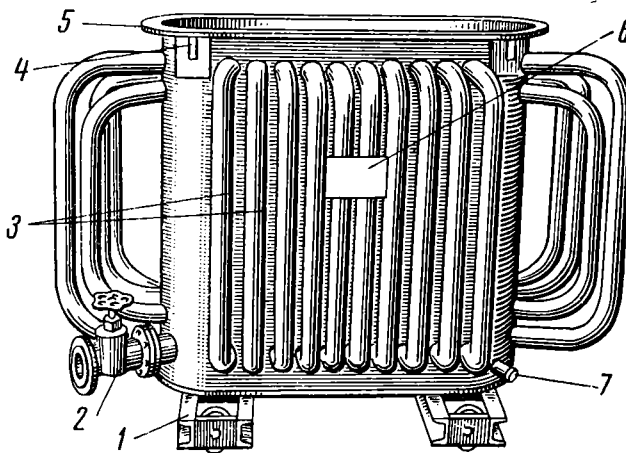


Fig. 10.9. Tubular tank of 250-kVA transformer

1—transformer transport bogey; 2—oil drain cock; 3—steel tubing; 4—lifting hook; 5—upper frame; 6—name-plate; 7—oil sampling plug

most closely the geometry of the transformer active components and is relatively simple to manufacture.

A smooth tank consists of a wall, bottom, and frame. The wall is made of steel sheets joined together by means of electric arc welding and then welded to the bottom of the tank. The frame, welded to the wall top, is made from a steel strip containing holes spaced equally apart. A cover, also fabricated from sheet steel, is bolted to the frame. A spacer which is a strip of oil-resistant rubber is interposed between the frame and the cover to render the joint leak-proof. The tank housing the active components of the transformer is filled with transformer oil.

The tubular tanks have round or oval tubes, the ends of which are welded into the walls. The appearance of a tubular tank with round tubes (power transformer of size II) is shown in Fig. 10.9,

The minimum internal dimensions of the tank are determined as shown in Fig. 10.10. The tank size in plan depends upon the outer dimensions of the active components and the minimum necessary insulation spacings from the windings and taps to the tank walls.

The insulation spacings in the power transformers designed for series production are determined from the data

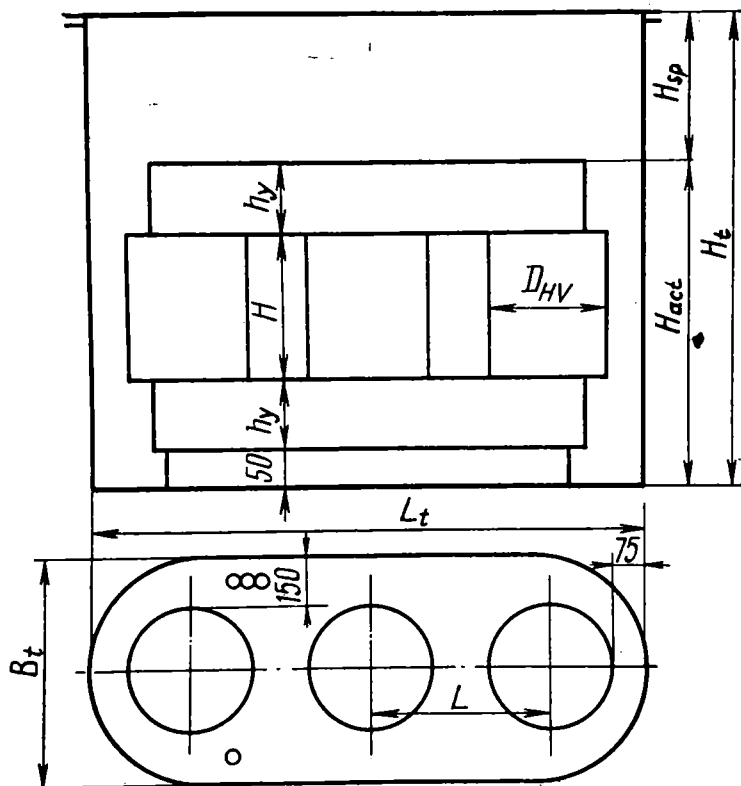


Fig. 10.10. Basic tank sizes

contained in the manufacturer's instructions or from the data given in Reference [2]. For the purposes of technical training in the computation of transformers of about 35 kVA, the spacing between the HV winding and the tank wall may be approximately taken as 150 mm opposite the broader wall on the side of taps and 75 mm opposite a rounded part of the wall.

Hence, the tank length

$$L_t = 2L + D_{HV} + 2 \times 75 \quad (10.12)$$

and breadth

$$B_t = D_{HV} + 2 \times 150 \quad (10.13)$$

The height (depth) of the tank is determined from the height of the active components of the transformer and the minimum spacing from the upper core yoke to the tank cover, sufficient to arrange lower parts of the bushing insulators, leads and switches (if the latter are attached to the under-

Table 10.4

Voltage class of HV winding, kV	Yoke-to-cover spacing (minimum) mm
6	270
10	300
20	350
35	470

side of the cover). The tank height is also dependent upon the voltage class of the HV winding.

Thus, the tank height is

$$H_t = H + 2h_y + H_{sp} + 50 \text{ mm} \quad (10.14)$$

where H = height of the core window, mm

h_y = yoke height (maximum), mm

H_{sp} = upper yoke-to-cover spacing (mm) taken from Table 10.4

50 mm = approximate spacing between the tank bottom and the lower yoke

The spacing from the yoke to the cover selected from Table 10.4 may be increased whenever it becomes necessary to increase the tank height from design considerations (say, for more rational arrangement of tubes and coolers).

Table 10.5

Number of tube rows	Multiplied by (K_{mult})
Smooth tank	1
1 row	2.8
2 rows	4.0
3 rows	5.2
4 rows	5.7

Proceeding from the determined basic dimensions of the tank (L_t , B_t , H_t), we can find the side wall area of the oval tank (refer to Fig. 10.10):

$$A_t = p_t H_t = [\pi B_t + 2(L_t - B_t)] H_t \times 10^{-6}, \text{ m}^2 \quad (10.15)$$

where p_t = tank wall perimeter in mm

The surface area of the oval tank cover is

$$A_{\text{cover}} = \left[\frac{\pi}{4} B_t^2 + (L_t - B_t) B_t \right] 10^{-6}, \text{ m}^2 \quad (10.16)$$

The use of the tubes increases the cooling surface area of the tank. The effective cooling surface of the tubular tank is always less than its geometrical surface because the convection heat transfer occurs from the entire surface of tubes while the heat transfer by radiation, only from the external side of tubes. Besides, the heat-transfer coefficient drops with an increase in the number of tubes, and consequently it is impracticable to apply more than four rows of tubes.

Varied sizes and shapes of tubes are used, for example, round tubes (outer diameters, 51 and 30 mm) and oval tubes (75×20 mm).

The effective heat-liberating surface of a tubular tank is calculated by determining the surface area of the tank wall and that of all the tubes. The obtained results are then multiplied by a cer-

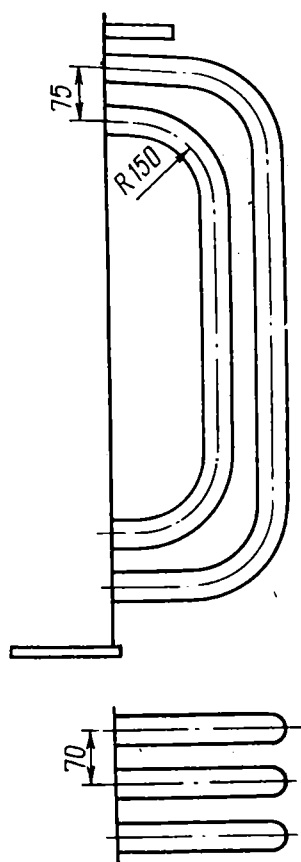


Fig. 10.11. Arrangement of round tubes on the tank wall

tain factor related to the number of tube rows applied.

In the case of 51-mm diameter tubes, the effective surface area of the tubular tank may be approximately determined by multiplying the surface area of the tank by a certain

multiplicity factor K_{mult} which allows for the increase in the cooling surface area (see Table 10.5).

The values of K_{mult} are given for such an arrangement of the tubes on the tank wall at which the spacing between

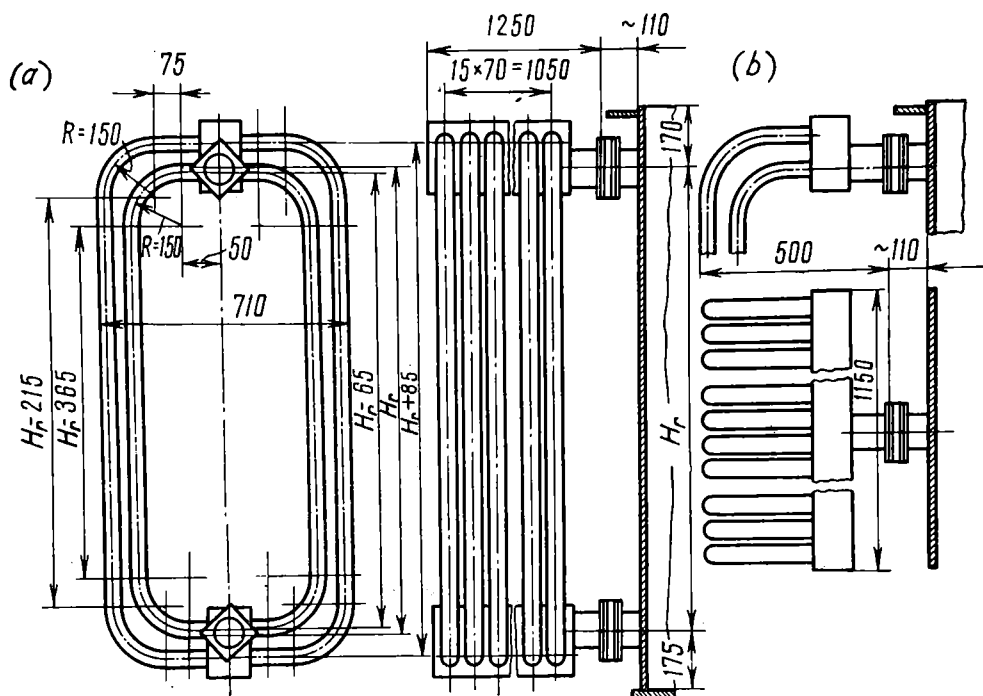


Fig. 10.12. Tubular cooler (radiator) for natural oil cooling
(a) double cooler, number of tubes $2 \times 2 \times 16 = 64$; (b) single cooler, number of tubes $2 \times 16 = 32$

the tube axes in a row is 70 mm and the rows are spaced 75 mm apart (Fig. 10.11).

If the tubes are arranged on the tank partially in two and also in three rows, the multiplicity factor will take up a certain intermediate value.

Suppose, for example, that 40 per cent of the wall area is covered with two rows of tubes, the remaining portion containing three rows. Then the multiplicity factor is

$$K_{mult} = \frac{4.0 \times 40 + 5.2 \times 60}{40 + 60} = \frac{160 + 312}{100} = 4.72$$

Thus the total cooling surface of the tubular tank is

$$A_{t.t} = K_{mult}A_t + 0.75A_{cover} \quad (10.17)$$

where 0.75 is the factor which allows for shielding a portion of the tank cover with terminals and other fittings.

The radiator tanks, as has already been stated, are provided with flanged pipes welded into the upper and lower parts of the tanks to receive the coolers (radiators).

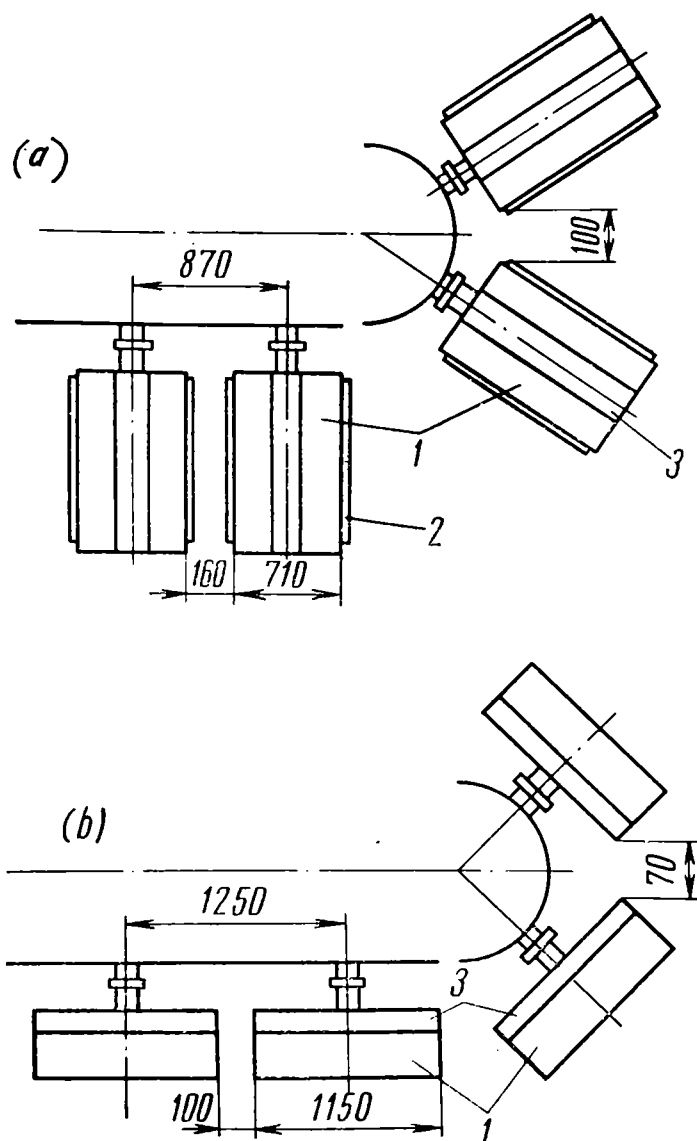


Fig. 10.13. Arrangement of coolers on the tank with minimum spacings between them

(a) radial arrangement of double coolers; (b) tangential arrangement of single coolers; 1—tubes; 2—corner plates; 3—manifold

Most commonly used is a double- or a single-tubular radiator (Fig. 10.12). These radiators employ 51-mm outer diameter tubes. As is clear from Fig. 10.12, the radiator consists of four (double) or two (single) rows of round tubes,

16 in each row. The tubes are bent on both ends in the same manner as for the tubular tank and welded into two square manifolds. The manifolds are fitted with two flanged pipe sockets for connecting the radiator to the transformer tank. The double radiators are arranged radially and the single radiators tangentially in respect to the tank wall. Accordingly, the pipe sockets are fastened to the manifold either on its end face or in the middle.

The arrangement of the coolers on the tank and the minimum spacings between them are shown in Fig. 10.13.

The sizes of the coolers are limited by the spacing between the axes of the pipe sockets. The type of a cooler is selected depending on the height and the perimeter of the tank whereas the number of coolers depends on the surface area to be cooled. In the cooler type designations the numerator

Table 10.6

Cooler type		Cooler effective surface area, m ²		Size H_r , mm	Minimum tank height $H_r + 345$ mm
single	double	single	double		
188/9.4	188/17.8	9.45	17.8	1880	2225
200/10	220/18.9	10	18.9	2000	2345
228.5/11.1	228.5/21.2	11.15	21.2	2285	2630
248.5/11.9	248.5/22.7	11.9	22.7	2485	2830
268.5/12.7	268.5/24.4	12.75	24.4	2685	3030
300/13.9	300/26.7	13.9	26.7	3000	3345
325/14.8	325/28.6	14.85	28.6	3250	3595
375/16.7	375/32.4	16.75	32.4	3750	4095

denotes the spacing H_r between the axes in cm, and the denominator indicates the surface area in m² (see Fig. 10.12).

The basic data of the tubular coolers is given in Table 10.6. The total cooling surface of the radiator tank is

$$A_{rad.t} = nA_{eff} + A_t + 0.75A_{cover} \quad (10.18)$$

where n = number of coolers

A_{eff} = effective surface area of cooler, m²

A_t = surface area of the smooth side wall of the tank, m²

10.7. Transient Heating

The temperature rises for the winding and oil determined as stated in Secs. 10.4 and 10.5 do not reach their steady values until after a certain period of time. The time during which overheating changes at a constant load and a constant ambient temperature is called the *period of transient heating*.

On connecting the load, the temperature of the winding and oil first rises exclusively on account of their thermal capacity because there is no heat transfer. If there were later no heat dissipation, the heating would proceed at a uniform

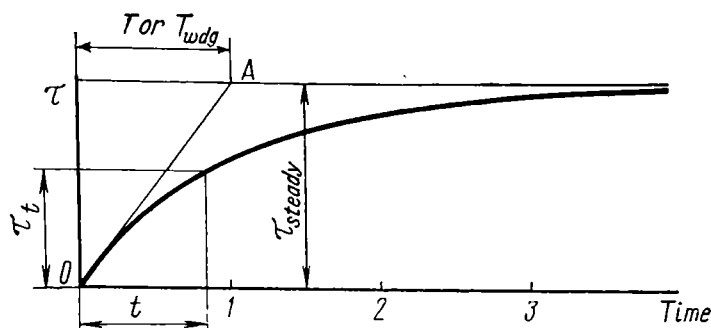


Fig. 10.14. Exponential heating curve

rate and the overheating of the winding and oil would reach a certain value corresponding to the given load after a definite time T_{wdg} (for the winding) and T (for the transformer oil) called the *time constant*.

In the chart shown in Fig. 10.14 this heating process would follow line OA . But actually the heating proceeds along a certain exponential curve. The heating curve is initially tangent to the straight section OA and then asymptotically approaches a straight line parallel to the abscissa axis and having the τ_{steady} ordinate. This is because the heat transfer gradually increases with time.

The temperature rise reaches its steady state practically after a time equal to 3 to 4 T . This is the point of thermal equilibrium; the amount of heat generated in the winding or transformer becomes equal to the heat transported through the winding or tank surface.

The exponential-curve equation (in the absence of initial overheating) is

$$\tau_t = \tau_{steady} (1 - e^{-\frac{t}{T}})$$

where τ_t = overheating at the instant of time t

τ_{steady} = steady overheating for a given load

T = time constant

In the general form the heating curve equation (with a certain initial heating τ_{in}) is

$$\tau_t = \tau_{steady} (1 - e^{-\frac{t}{T}}) + \tau_{in} e^{-\frac{t}{T}}$$

The time constant of the winding

$$T_{wdg} = \frac{c_{cu}}{P_{sc}} = \frac{C_{cu} G_{cu} \tau_{wdg}}{P_{sc}} K_{ins, min}$$

where $c_{cu} = 6.6 \frac{\text{W} \cdot \text{min}}{\text{kg} \cdot ^\circ\text{C}}$ is the copper specific heat

C_{cu} = full heat capacity

G_{cu} = copper weight, kg

$K_{ins} = 1.2$ to 1.25 is the coefficient allowing for the thermal capacity of turn insulation

The transformer time constant

$$T = \frac{\Sigma c G \tau}{\Sigma P} = \frac{0.12 \left(G_{cu} + G_{st} + \frac{2}{3} G_t \right) + 0.5 G_{oil}}{P_o + P_{sc}} \times \tau_{oil}, \text{ h}$$

where G_{cu} = weight of copper, kg

G_{st} = weight of steel, kg

G_t = weight of tank, kg

G_{oil} = weight of oil, kg

The time constant of the oil-immersed power transformers is usually 2 to 4 hours.

By using the formulae of heating and time constants for the winding and the oil, their overheating can be determined at any moment of the transient heating state. The converse is also true and we may determine the time after which the winding temperature reaches the permissible value in the case of overloading, which is often required in transformer service.

Review Questions

1. What is the purpose of transformer cooling?
2. What standard overheating values are established for windings and oil?
3. What methods are applied for measuring the winding and oil temperature?
4. Why are the winding and oil temperatures rise rather than their absolute temperatures determined in the process of thermal computation?
5. Describe the stages of heat transfer from the winding into the surrounding air.
6. What causes oil to circulate in the tank and cooling devices?
7. Why do larger transformers require more complicated cooling devices?

Chapter Eleven

Magnetic Cores. Types and Construction

11.1. Electrical Steel

The transformer core is a closed magnetic circuit through which passes the main magnetic flux (Φ) linking both windings. The properly designed core is the one which has the least no-load currents and power loss. To this end, the steel used for core production should possess high permeability, high resistivity and low coercive force. So, the better the steel properties, the higher the quality of a transformer in general.

The cores of modern power transformers are stacked from thin sheets of special silicon steel (0.35 and 0.5 mm thick) consistent with the standard requirements.

The steel used for construction of transformer cores may be hot-rolled and cold-rolled.

The hot-rolled steel sheets 0.5 mm thick which permits induction B in the core from 1.4 to 1.45 teslas were in use for a considerable length of time. In recent years this type of steel has completely been superseded by 0.35-mm thick cold-rolled steel sheets allowing for 1.6 to 1.7 teslas. The increase in induction makes it possible to save ferromagnetic materials, although cold-rolled steel is somewhat more expensive (by 25—35 per cent) than hot-rolled steel. Apart from that, the use of cold-rolled steel involves a more complicated core construction and requires new methods of machining the laminations.

The cold-rolled steel exhibits anisotropical characteristics attained by a special technology of steel rolling. Magnetic anisotropy means that the specific losses are brought to a minimum and permeability to a maximum when the magnetic flux lines coincide with the direction of rolling. However,

to utilize the properties of electrical steel to the utmost, the core laminations must be cut to an appropriate shape without holes for clamping bolts and pins and stacked into an assembly with the aid of mitre joints (Fig. 11.1b).

The electrical steel is usually supplied in sheets 750×1500 mm and 1000×2000 mm in size. However, to render the process of cutting laminations and manufacturing cores fully automatic, the cold-rolled grain-oriented steel may be also delivered in rolls 240, 750 and 1000 mm wide.

The electrical steel laminations prepared for core assembly should be insulated from one another. The most common

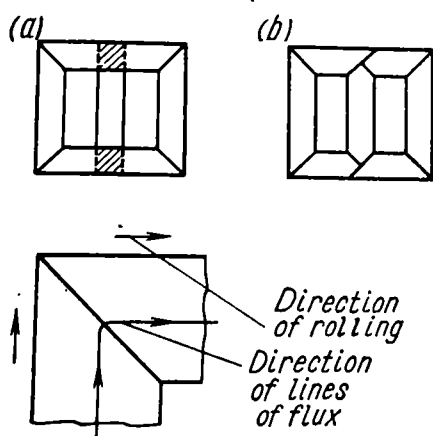


Fig. 11.1. Core and yoke lamination joints

(a) combination of right-angled and mitre joints; (b) mitre joints

practice is to coat laminations with a thin film of varnish on both sides. The varnishing may be single, double, or threefold depending on the transformer capacity (core-circle diameter). In recent years it has become usual to apply a double-sided heat-resistant coating of the steel sheets at the metallurgical plants immediately after rolling. This coating is particularly advisable if the laminations are to be annealed after finishing in order to remove work hardening. Besides, the heat-resistant coating assures the highest space factor.

The intersheet insulation diminishes the factor of filling the leg and yoke geometric cross-sectional areas with ferromagnetic steel. The space factor K_{sp} is the ratio of the net-cross-sectional area of the steel laminations (effective leg section A_{leg} and yoke section A_y) to the area of a stepped

contour of the core ($A_{leg. step}$ and $A_{y. step}$), i.e., $K_{sp} = A_{core eff}/A_{core step}$.

The space factor K_{sp} depends on the thickness of the steel laminations, type of intersheet insulation, degree of sheet compression, as well as on such defects as transverse (corrugation) and longitudinal (warping) deformation, etc.

Table 11.1

Steel supplied as	Insulation	Space factor for sheet thickness (mm)	
		0.5	0.35
Sheets	None	0.97—0.98	0.95—0.96
	Single varnishing	0.95—0.96	0.93—0.94
	Twofold varnishing	0.93—0.94	0.91—0.92
	Threefold varnishing	0.91—0.92	0.89—0.90
Coils	Heat-resistant coating	—	0.95—0.96
	Heat-resistant coating and single varnishing	—	0.93—0.94

- The space factor (even if there is no coating) is always less than unity. The averaged values of the space factor at normal compression are given in Table 11.1.

11.2. Core Types of Single- and Three-Phase Transformer

The single-phase transformer has the core of two basic types. The core-type transformer is shown in Fig. 11.2 and the shell-type is illustrated in Fig. 11.3. When the magnetic circuit takes the form of two legs surrounded with windings and two yokes closing the legs from top and bottom, the transformer is core-type. Each leg carries both the HV and LV windings, each divided in two portions. The arrangement of the HV winding on one leg and the LV winding on the other is objectionable because of a sharp intensification of ⁵ reactance drop V_l due to large leakage fluxes. The shell-type transformer has a distributed magnetic circuit with a

central iron around which the coils are wound. The leg is enclosed in yokes. In view of the fact that the magnetic flux leaving the core is branched off in two paths, each yoke section of the shell-type transformer is taken to be one half of the leg section.

• Shell-type magnetic circuits are mostly employed for single-phase transformers of low capacity whereas core-type

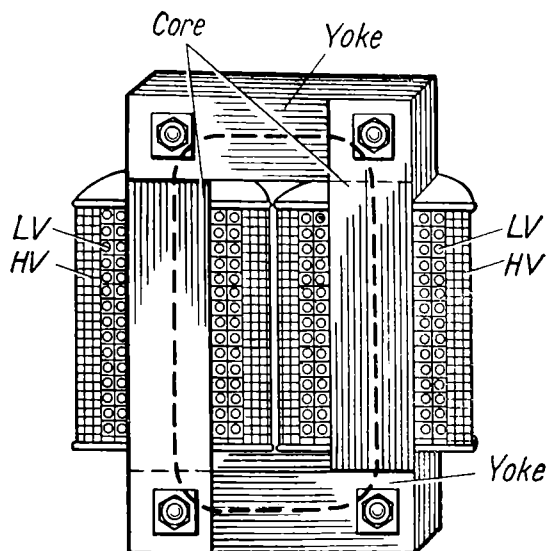


Fig. 11.2. Single-phase core-type transformer

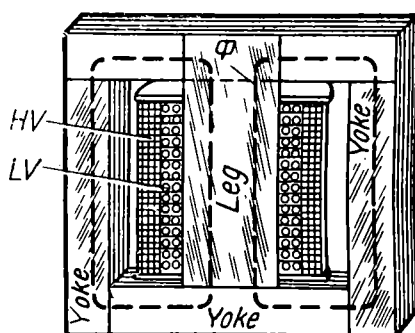


Fig. 11.3. Single-phase shell-type transformer

magnetic circuits are preferable for power transformers which require a large cooling surface and where dissipation should be reduced by nearly 50 per cent.

Essential features of a three-phase magnetic circuit are discussed below.

Electric power is generated and utilized for industrial purposes mostly in the form of a three-phase AC system which is actually a system of three single-phase variable EMFs having a similar frequency and shifted in phase by 120° , i.e., one-third of a period with respect to one another.

It is obvious that the three-phase current may be transformed through a bank of three single-phase transformers, each winding being connected in one of the three-phase circuits (either star or delta).!

Moreover, the three-phase transformation is also possible through the medium of one three-phase transformer having

a magnetic circuit common to all three phases. This fact was established back in 1891 by the Russian engineer M. Dolivo-Dobrovolsky.

A three-phase magnetic circuit may be obtained by combining three individual single-phase core-type circuits into a common circuit with some further change of its configuration. For this purpose, three single-phase cores, each having one coil-carrying leg, should be disposed as shown in Fig. 11.4*a*, with unwound (free) legs facing one another. To simplify the drawing, each core is shown with a single solid

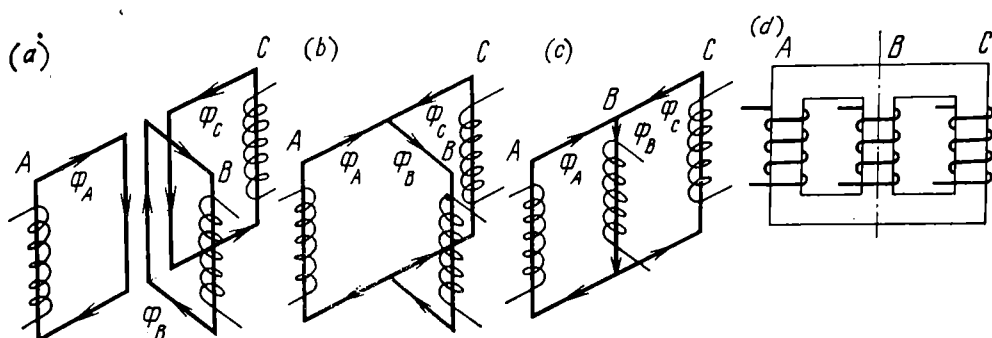


Fig. 11.4. Arrangement of three-phase, three-legged transformer from three single-phase core-type units

line. By virtue of the fact that all the magnetic core fluxes are sinusoidal in wave-form, equal in magnitude and shifted in phase through 120° , we can apply the sine sum formula and obtain $\sin \alpha + \sin (\alpha + 120^\circ) + \sin (\alpha + 240^\circ) = 0$, that is, the sum of fluxes in the adjoining legs is zero and therefore these legs may be omitted. Now, we can convert the three-dimensional symmetrical core figure into a flat figure (Fig. 11.4 *b, c*) and obtain a conventional form of a three-phase core-type magnetic circuit now in use (Fig. 11.4 *d*).

The three-phase core-type circuit is unbalanced with regard to the magnetic resistance for the fluxes of the mid and extreme phases. This is illustrated in Fig. 11.5.

The flux of phase *B* follows a shorter path than the fluxes of phases *A* and *C*. Hence, the magnetic resistance for the flux of mid phase *B* is approximately 2 to 2.5 times less than that for the extreme phases *A* and *C*. Therefore, the

no-load current for phase *B* will be also smaller than for other phases.

As the phase open-circuit currents of the three-phase transformer are unequal, the average value of the open-circuit

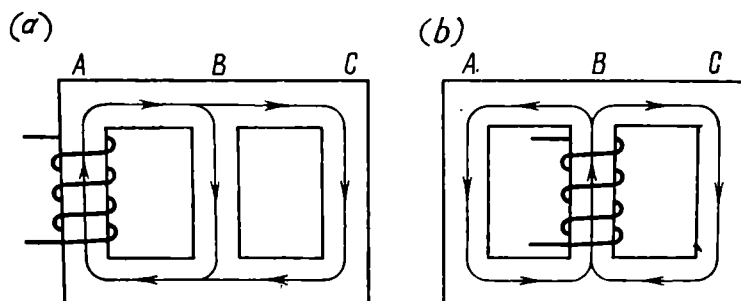


Fig. 11.5. Paths of magnetic fluxes of different phases in three-phase unbalanced core-type transformer

currents for all the three phases, when conducting no-load tests, is taken as

$$I_0 = \frac{I_{0A} + I_{0B} + I_{0C}}{3}$$

The average value of the open-circuit current is also determined when calculating the open-circuit current of the three-phase transformer because here the total weight of the core steel and the total number of joints in laminations are taken into account.

11.3. Butt-Joint and Interleaved Core Assemblies

Power transformer cores are assembled from separate laminations. The simplest way to stack the laminations is illustrated in Fig. 11.6 *a* in which the legs and yokes constituting the magnetic circuit are first assembled separately and then clamped together (butt-joint assembly).

Unfortunately, this type of assembly suffers from serious shortcomings. Thus, to prevent the core and yoke laminations from being shorted at the point of joint, an insulation spacer should be fitted in between (Fig. 11.7 *b*). However, the spacer increases reluctance of the magnetic circuit, which leads to a rise in magnetizing current. Should the

insulating spacer be damaged, the short occurring between the core and yoke laminations would lead to the so-called steel burning causing thereby transformer failure.

The above deficiencies limit the application of the butt-joint assembly and therefore the method of interleaving

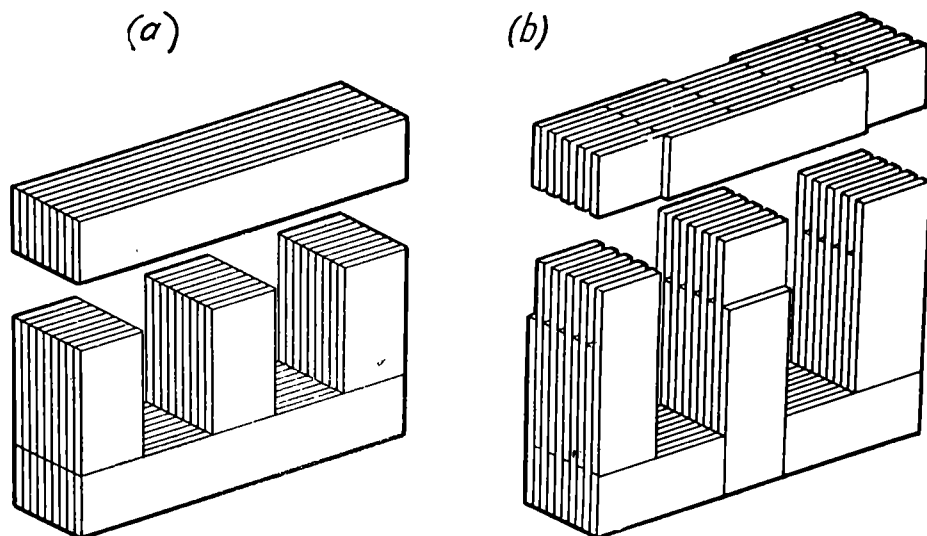


Fig. 11.6. Core assemblies
(a) butt-joint assembly; (b) interleaved assembly

laminations has been adopted for power transformers of all ratings in the transformer-building industry. The interleaved construction provides for greater sturdiness of the entire

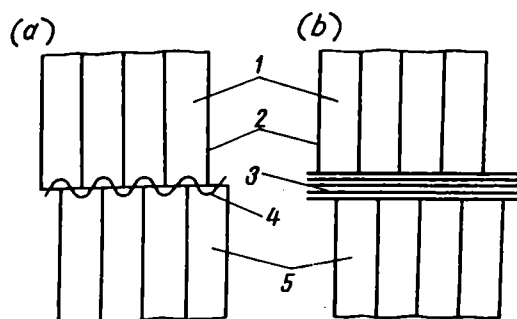


Fig. 11.7. Butt joints of core and yoke

(a) without insulating spacer; (b) with insulating spacer; 1—yoke lamination; 2—insulation of laminations; 3—insulating spacer between yoke and core; 4—eddy current path; 5—core laminations

magnetic circuit, requires a smaller amount of fasteners and is more reliable in service.

The interleaved core is assembled from individual stacks, each consisting of several laminations arranged in a definite manner. All the even stacks have one position of the lamina-

tions and all the odd stacks have a reverse (image) position, so that laminations of one stack may overlap the joints of the adjacent stacks.

Thus the laminations of adjacent stacks form an interwoven pattern (Fig. 11.6 b).

11.4. Patterns of Interleaving Single- and Three-Phase Magnetic Circuits

The interleaving diagrams of single- and three-phase core-type magnetic circuits are shown in Figs. 11.8 and 11.9.

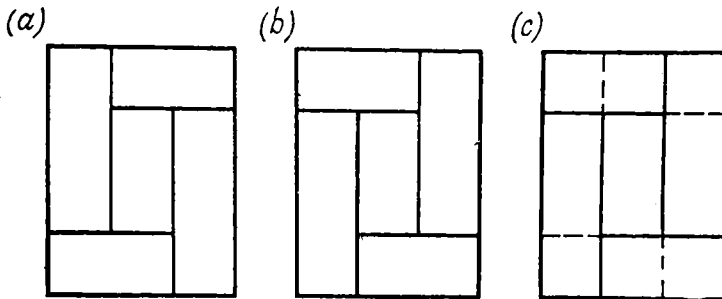


Fig. 11.8. Patterns of interleaving laminations of single-phase core
(a) 1st position (odd laminations); (b) 2nd position, image of the 1st position (even laminations); (c) overlapping the joints

When the whole structure is interleaved, the yokes and legs form as if a single whole. But in order to place the

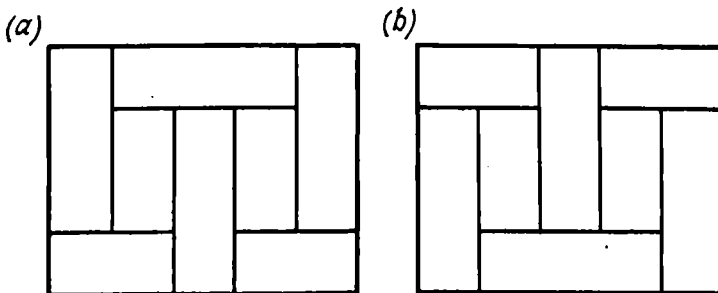


Fig. 11.9. Patterns of interleaving laminations of three-phase core
(a) 1st position (odd laminations); (b) 2nd position, reverse of the 1st position (even laminations)

windings on the legs, which is the first stage of transformer assembly, the upper yoke should be disassembled, and after fitting the windings on the legs, re-assembled.

• Some manufacturers disposed with the upper yoke disassembling operation for transformers size I by combining the operations of core interleaving and the first stage of transformer assembly into one operation, whereby the core and

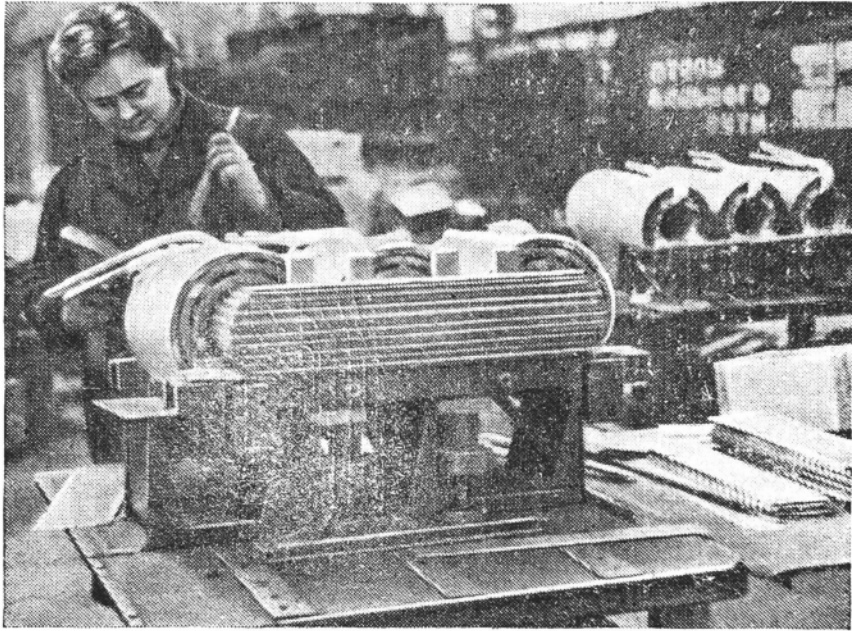


Fig. 11.10. Assembly (interleaving) of the core directly with windings

yoke are interleaved directly with horizontally-positioned windings (Fig. 11.10).

Besides, some manufacturers do not interleave the upper yoke in the small-size transformers during assembly of the magnetic circuit and place the yoke bars on the pins beneath the expected interleaving in order to lift the yoke.

11.5. Effects of Types of Interleaving and Air Gap Sizes on No-Load Characteristics

To accelerate the magnetic circuit assembly, layers containing not one but two or three and even more insulated laminations are interleaved at a time. In this case the interleaving patterns remain unaltered although the thickness of each layer grows accordingly two or three times. Here it should be pointed out that the increased thickness of the

layer augments no-load currents and power losses of the transformer because of the increased magnetic resistance offered to the magnetic lines bypassing lamination joints, as is seen in Fig. 11.11 *a* and *b*. The more laminations are in the layer, the greater the number of the magnetic lines that cut through the air (non-magnetic) gaps between the leg and yoke laminations.

Since the magnetic flux must pass through the air gaps in the joints of the laminations (both in the butted and interleaved assemblies of the magnetic circuit), the gap

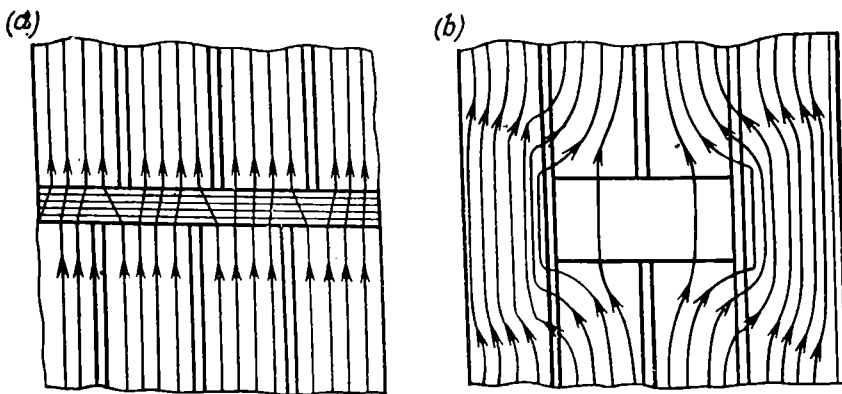


Fig. 11.11. Shapes of non-magnetic (air) gaps

(a) in butt-joint core assembly; (b) in interleaved core assembly (a layer consists of two laminations). Arrows indicate direction of magnetic lines

sizes severely affect the magnitude of transformer magnetizing current.

To reduce the magnetizing current, the interleaving at the lamination joints should be done with utmost care. The gaps between the laminations must not be greater than 1 or 2 mm. Otherwise, the gaps should be filled to obtain the required size or, if it does not help, the interleaving process should be repeated.

It has already been mentioned that the cold-rolled electrical steel has the maximum magnetic permeability in the direction of rolling. Therefore, if the cores and yokes were stacked of interleaved right-angled laminations the magnetic lines at the corners of the magnetic circuit would be turning at an angle to the axis of laminations, thus giving rise to power losses and magnetizing force (Fig. 11.12 *a*, *b*).

This effect is minimized by making bevelled (mitre) joints between the laminations (Fig. 11.12 c).

However, these mitre joints greatly complicate the manufacture of laminations and assembly of the entire magnetic

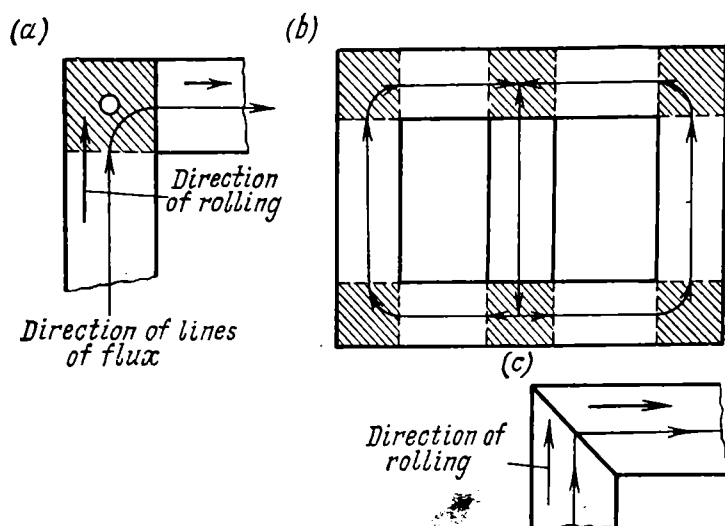


Fig. 11.12. Portions of core made of cold-rolled steel, in which increased losses are due to right-angled joints (a and b) and minimized losses, due to mitre joints (c).

circuit, making these operations more cumbersome. This is why the mitre joints have not yet find extensive application in the domestic transformer-building industry. The combined use of right-angled and mitre joints may simplify the construction to a certain extent (refer to Fig. 11.1 a).

Review Questions

1. Name the basic grades of electrical steel used in transformers.
2. Define and draw the core-type and shell-type transformers.
3. Explain the construction of the three-phase core-type magnetic circuit. Why is this circuit called asymmetrical?
4. What are the advantages and disadvantages of the interleaved core-and-yoke structure as contrasted with the butt-joint assembly?
5. How much effective are the mitre joints used in the magnetic cores assembled from cold-rolled steel laminations?

Types and Construction of Windings

12.1. General

The transformer winding is a constituent part of an electric circuit (be it primary or secondary). The winding is composed of a conductor material (copper or aluminium wire) and insulation.

The winding system also includes terminals, voltage-regulating taps, capacitive-protection rings and electrostatic shields providing overvoltage protection.

The winding design is mainly determined during computation of transformer design parameters when a particular type of winding and all the winding data, namely, the number of turns, sizes of wire, cooling ducts, insulating cylinders, insulating barriers and the like, are chosen. The winding data chosen should be well correlated with the electromagnetic, insulating and thermal characteristics of the transformer.

The calculation of a winding is aimed at providing the most rational arrangement of the desired number of winding turns in the core window, which depends to a great extent on a correctly chosen type of winding. The choice of a type of winding is governed by the requirements imposed on the winding as well as the production possibilities of its manufacture.

A properly constructed winding should satisfy the following requirements:

- (a) minimum load losses with best utilization of copper;
- (b) adequate mechanical strength;
- (c) sufficient heat resistance;
- (d) sufficient electric strength of insulation.

Apart from that, there are economical factors to be reckoned with to which are related the least production expenses and also the simplicity of construction.

12.2. Conductor Material and Types of Windings

The basic conductor material used for transformer windings is the insulated copper or aluminium wire of round or rectangular cross section.

The sizes (diameters) of the round wire used in transformers are given in the table of diameters for winding copper specified by standards. The wire diameters in practical use are 0.2 to 4.1 mm.

The wire insulation differs with wire diameter and requirements for the winding. There are varied grades of wires as to their insulation. The enamel-coated wire of 0.2 to 1.3 mm in diameter is used for small-size cores. If it is desired to have insulation of greater strength and heat resistance, use is made of wire covered with extremely strong viniflex enamel. For power transformers rated at 10 kVA and more and small-capacity transformers of increased dependability (transformers of vibration- and shock-proof design), it is best to use enamel-coated wires covered with silk (caprone), terelene or cotton materials.

Wires of up to 0.35 mm in diameter are covered with caprone or terelene and those of 0.38 to 1.3 mm, with cotton. 1.3 to 4.1-mm diameter wires are insulated with a few layers of cable paper.

Heat-resistant windings require appropriate wire: the two-layer-glass-fibre coated wire and the same wire but impregnated with silicon-base varnish.

Rectangular conductors are insulated with cable or telephone paper. Heat-resistant wires are covered with glass-fibre insulation.

The rectangular conductor sizes (thickness a and width b) are standardized as are the round conductor diameters. It is usual to apply the conductors with size a varying from 1.25 to 5.6 mm and b , from 4.0 to 14.0 mm. The ratio of sizes a and b is optional (as specified in Table 3.2). However, it is not advisable to select the conductor section close to a squ-

are ($a \approx b$), as during wind operations this conductor tends to stand edgewise, causing damage of the conductor insulation. Apart from that, the larger and smaller sides of this conductor are hard to tell by eye.

The effective sectional area given in Table 3.1 is somewhat less than the product ab (by 0.215 to 0.86 mm²). This reduction in section is caused by a slight rounding of corners, which is essential to prevent the damage of turn insulation at the corners.

The winding consists of turns of the winding conductor wound round the core leg. The choice of the turn section depends on the rated load current. The round conductor is used in the case of small currents and the rectangular conductor (one or more parallel conductors) for larger currents.

The choice of the number of turns of the winding depends on the value of voltage. Individual winding turns are grouped into coils. The coil comprises a definite number of turns wound during a single operation on the winding machine. Each winding may comprise one or more interconnected coils.

When the coil is wound on the winding machine, each subsequent turn may be placed either adjacent to or over the preceding turn (the latter will be practicable only in the case of rectangular conductors). Thus different types of windings are produced. In the former case the winding has a cylindrical form called the *cylindrical layer winding* and in the latter case the *disc winding*. (*sandwich*).

The rest of the windings represent the varieties or combinations of the two basic types.

12.3. Hand of Coil Turns

It was stated above in Sec. 2.3 that the connection (phasor) group depends upon the direction of winding the coils. There are two directions of winding, progressive (right-handed) and retrogressive (left-handed).

The direction of winding of a one-layer coil is assumed to be left-handed if the rake of the turns coincides with the left thread of a bolt and, accordingly, the right-hand direction follows the right thread. In the case of a left-hand wind of the layered coil, if viewed from the end face, the wire of

the coil runs from the beginning of winding in a counter-clockwise direction. Similarly, the wire of the right-handed coil runs clockwise. This rule will be also true for a multi- 5 layer coil and it will be called either left-handed or right-handed, depending on the hand of winding of its first layer.

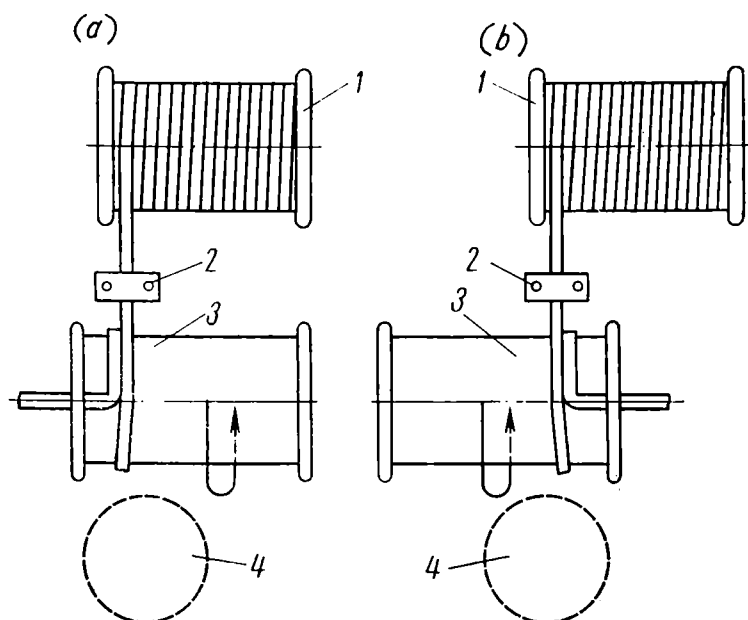


Fig. 12.1. Diagrams of winding the layer coils

(a) left-handed; (b) right-handed; 1—winding-wire drum; 2—wire tensioning blocks; 3—former; 4—winder's position

It should be pointed out that in the case of multilayer 6 coils, the direction of winding of the odd and even layers is alternating.

When the layered coils are wound on the winding machine, and the winder's position is on the side opposite to the drum, the wind of the layer will be left-handed if this layer is wound starting from the left side of the former and, on the contrary, it will be right-handed if the wind is started from the right.

The winding of the left and right coils is schematically shown in Fig. 12.1.

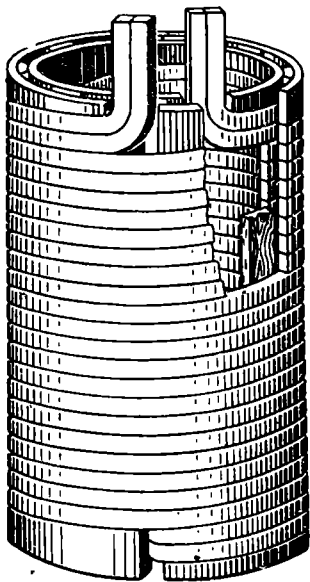
The layered coils are usually made left-handed, unless specified otherwise, which is somewhat convenient from technological considerations.

12.4. Cylindrical Layer Winding

The layered winding is made of both round and rectangular conductors wound in one, two or more layers and is called accordingly the one-, two- or multi-layer winding.

The winding made of rectangular conductors may be simultaneously wound from one or more parallel conductors

placed flatwise or edgewise. If the voltage is low (up to 690 V), the winding is usually wound directly round the former (holder).



The rectangular-conductor windings are mostly made two-layered because in this case it is easier to secure the lead-out ends. Placed between the layers is the insulation barrier made from press-board material, or an oil cooling duct (for oil-cooled transformers) is provided, depen-

Fig. 12.2. Two-layer cylindrical winding made of rectangular conductors

ding on the cooling conditions chosen (Fig. 12.2). The duct width for the oil-cooled transformers is selected from Table 12.1.

The ducts are formed by means of battens fabricated either from pieces of press-board, cemented together, or from hard wood with pressboard strips 0.5 mm thick stuck in between the wood battens and the copper sides (Fig. 12.3 *a, b*). At the winding end-faces the helical surface of the extreme turn in each layer is level-

Table 12.1

Height of the manufactured winding, mm	Duct width, mm
up to 300	5
300-350	5.5
350-400	6
400-450	6.5
450-500	7
500-600	8

led either by means of pressboard strips or rings cut from a bakelite cylinder. These strips and rings are wedge-shaped (in the developed view) in order to fill in the empty space formed due to a large width of the turn,

particularly, when the turn consists of a few parallel conductors. The width of the wedge (Fig. 12.4 and 12.5) should be $\frac{H_a - H_d}{2}$ at one end, and $\frac{H_a - H_d}{2} + h_t$ at the other,

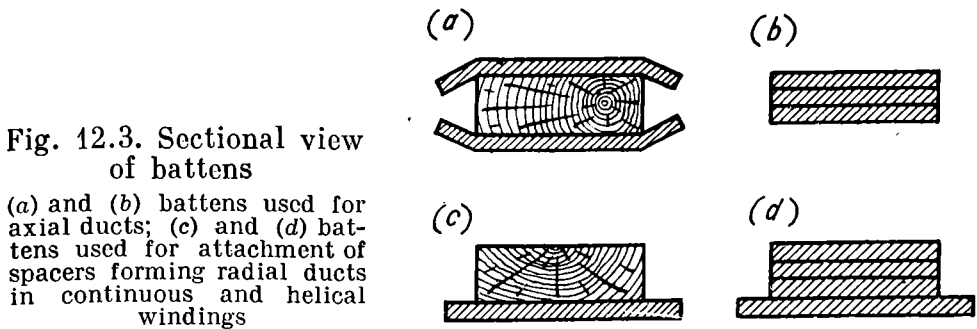


Fig. 12.3. Sectional view of battens

(a) and (b) battens used for axial ducts; (c) and (d) battens used for attachment of spacers forming radial ducts in continuous and helical windings

where H_a and H_d are correspondingly the actual and design heights the winding; h_t is the turn width.

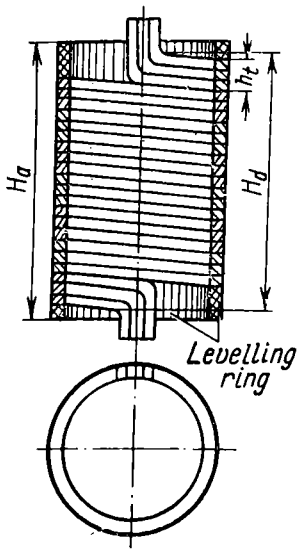


Fig. 12.4. Sectional view of cylindrical layer winding. Position of levelling ring

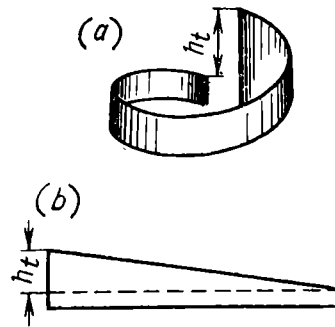


Fig. 12.5. Bearing (levelling) ring of cylindrical winding

(a) split ring cut out of bakelite paper cylinder; (b) press-board wedge (developed view)

A fairly large width of the turn (at currents of 1500 to 2000 A) causes an appreciable axial asymmetry between the HV and LV windings, due to a considerable resultant shortening of the LV winding. In this case, it is usual practice to

shift half of the parallel conductors which form the turn section through 180° along the circumference (Fig. 12.6). If such is the case, the levelling wedges are made as the

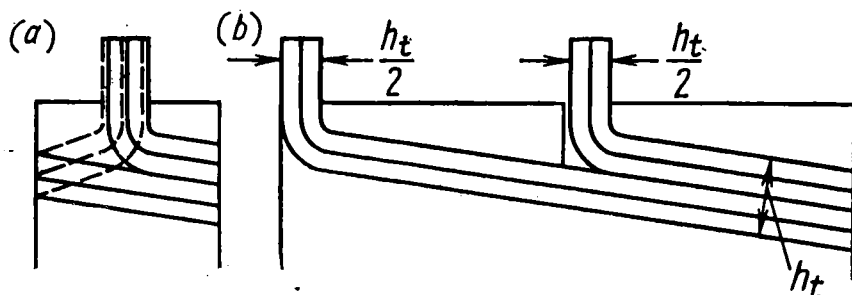
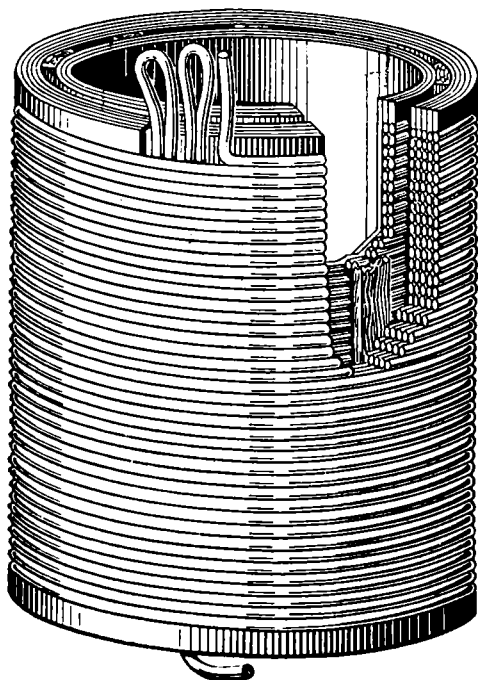


Fig. 12.6. Shifting half the parallel conductors by 180° to compensate for shortening of cylindrical winding
(a) actual view; (b) developed view

semirings. When connecting the leads, the wires shifted to the opposite side of the winding are thrown over the upper yoke for connection with the remainder wires on the LV side.



The layered winding made of round conductors (usually it is a multilayer winding (Fig. 12.7) is wound on the bakelite cylinder. The extreme turns are commonly secured in two ways: (a) taping the extreme turns with telephone paper (Fig. 12.8a) and (b) using the collars (Fig. 12.8b).

The collar 6 is actually a strip of pressboard stuck to a

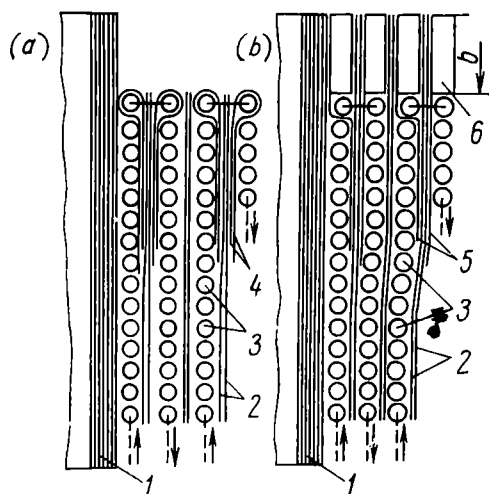
Fig. 12.7. Multilayer cylindrical winding made of round conductors

wider strip of telephone paper. The protruding portion of paper is held up with the extreme turns, preventing the collar from slipping. The breadth b of the collar for a voltage of 12 kV is 12 mm.

Cable paper 0.12 mm thick is used as an interlayer insulation barrier. The thickness of the interlayer insulation for the HV multi-layer windings mainly used in transfor-

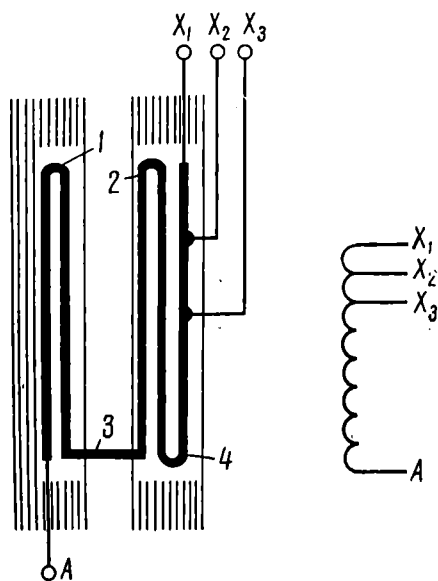
Fig. 12.8. Interlayer insulation and attachment of extreme turns of multilayer winding made of round conductors

(a) taping the extreme turns with telephone paper; (b) use of attachment collars; 1—bakelite paper cylinder; 2—interlayer insulation with cable paper 0.12 mm thick; 3—wire; 4—telephone paper 0.05 mm thick; 5—strip of telephone paper 40 to 60 mm thick; 6—pressboard collar



mers of sizes I and II (up to 400 kVA) is 2×0.12 mm at 6 kV and 3×0.12 mm at 10 kV.

To increase the cooling surface, a longitudinal duct is constructed after winding approximately one third of the total number of layers. This duct is made like in the case of the rectangular-conductor windings by means of the battens.



The HV winding made of rectangular conductors and used for transformers of sizes I and II is usually wound and connected as shown in Fig. 12.9. The line lead A taken from

Fig. 12.9. Diagram of cylindrical multilayer HV winding for 6 and 10 kV

the inner layer of the winding affords a better capacitive voltage gradient and thus provides good lightning protection (refer to Sec. 13.8).

Moreover, arrangement of regulating taps X_1 , X_2 and X_3 in the outer layers to effect the voltage adjustment within ± 5 per cent is more convenient as this simplifies the

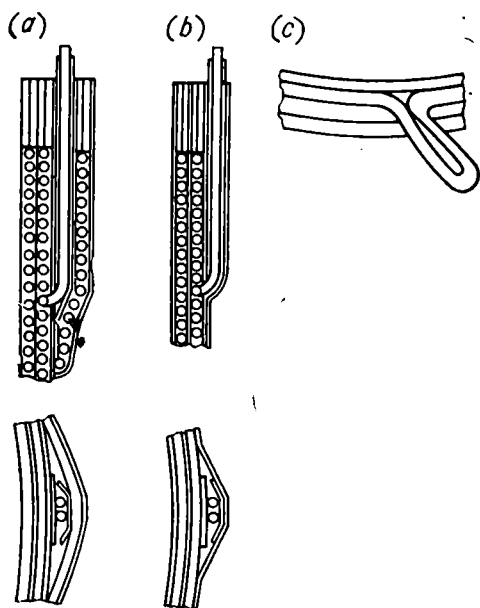


Fig. 12.10. Position of taps in cylindrical multilayer winding

(a) under the upper turn layer; (b) under the herringbone tape covering; (c) tap in the form of a loop

connection of taps to the switch. In the case of a round conductor, it is usual to make the taps in the form of loops. It should be stressed that the taps and notably the start wire should be well insulated (Fig. 12.10).

12.5. Coil-Type Layer Winding

With the use of a cylindrical multilayer winding at high voltages, the voltage between the layers may also be fairly high which makes it difficult to select a proper thickness of the interlayer insulation. To reduce the interlayer voltage, the winding may be axially separated into several multilayer coils.

The coils may be closely wound either on a common bakelite cylinder, spaced by the plain or cupped washers, or separately on bakelite rings. When the coils are wound separately, it is possible to improve their cooling by inserting the insulating spacers between the coils and thus constructing the cooling ducts.

It is customary to make the coil windings as the double (twin) coils, with the start leads interconnected in series. This connection helps to avoid bringing out the coil inner ends outward, which would impair the insulating conditions and complicate the winding construction.

Figure 12.11 shows a sectional view of the coil windings wound on a common cylinder (a) and separately (b, c).

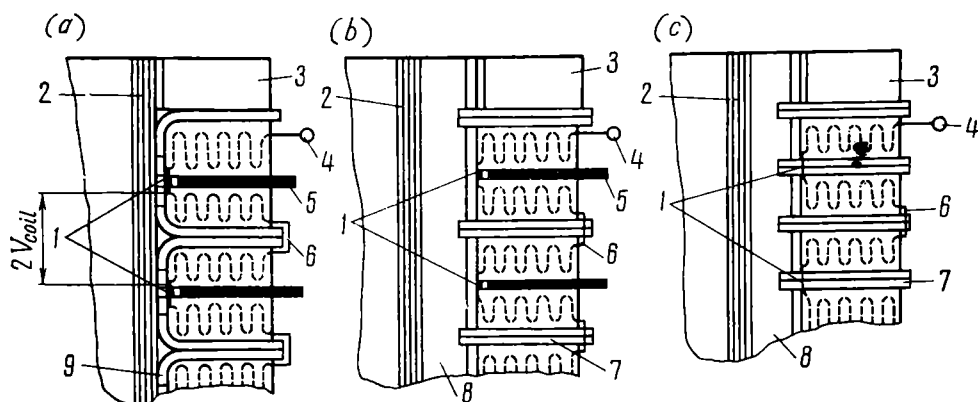


Fig. 12.11. Sectional view of coil layer winding

(a) with no ducts between coils; (b) with ducts between double coils; (c) with ducts after each coil; 1—internal coil connections (transitions); 2—bakelite paper cylinder; 3—pressboard bearing ring; 4—HV winding start; 5—spacer; 6—external connection (transition); 7—intercoil duct-forming spacers; 8—batten, forming a vertical duct; 9—cupped spacer (bent inwards)

The purpose of cupped spacers 9 is to increase the insulating overlapping space between two coils. As is apparent from Fig. 12.11a, the voltage between the two coils at the cupped portions of the spacers equals the sum of voltages in two coils ($2 V_{coil}$). That is why, the maximum spacing is required at these points.

12.6. Disc and Continuous Windings

Disc windings are intended primarily for use with large transformers. They consist of flat coils or discs connected either in series or in parallel. The disc coils employ rectangular conductors and are mostly assembled into double coils because this provides a more convenient connection of the inner ends.

Usually the double disc windings are wound from an entire length of wire. Each coil is wound starting from the middle, i.e., from the connection point of coils, until a double coil is formed (Fig. 12.12). It is customary to construct cooling ducts between the coils.

The advantage of the disc windings (or continuous and helical windings which have similar design) over the layer

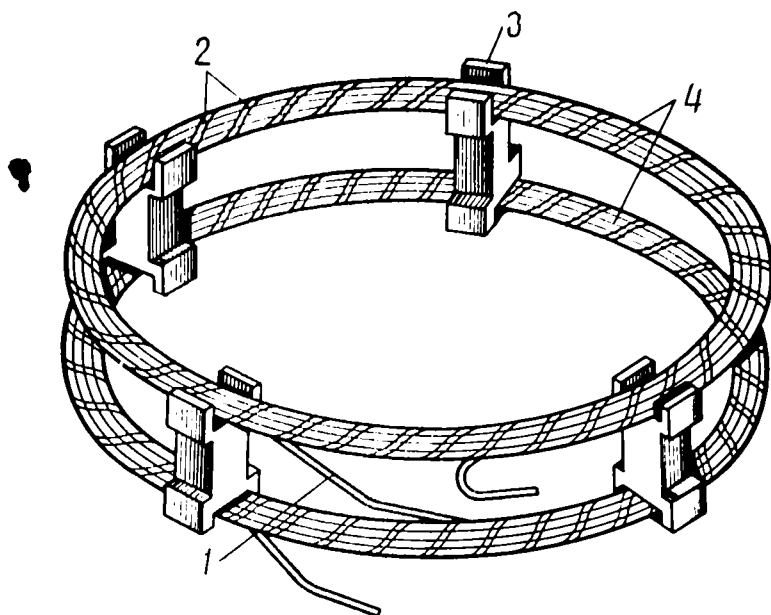


Fig. 12.12. Double disc coil

1—internal transition point; 2—covering; 3—temporary supports facilitating the covering of coil with herringbone tape; 4—single coils

and coil windings is a greater mechanical axial strength, although the layered windings are less expensive and easier to produce.

If the winding comprises a number of series-connected disc coils, it can be wound continuously, that is, without breaking the wire between the separate coils. Thus we obtain the so-called continuous disc winding (Fig. 12.13).

A distinguishing feature of the continuous windings is the use of transposition coils. The purpose of these coils is apparent from Fig. 12.14, where all the odd-numbered coils are the transposition coils. These coils are initially wound in the ordinary manner, beginning from the cylinder and outward, but then the turns of these coils are transposed in the

reverse order. To make the reversing easier, the wire should be somewhat slackened and then, after transposing the turns,

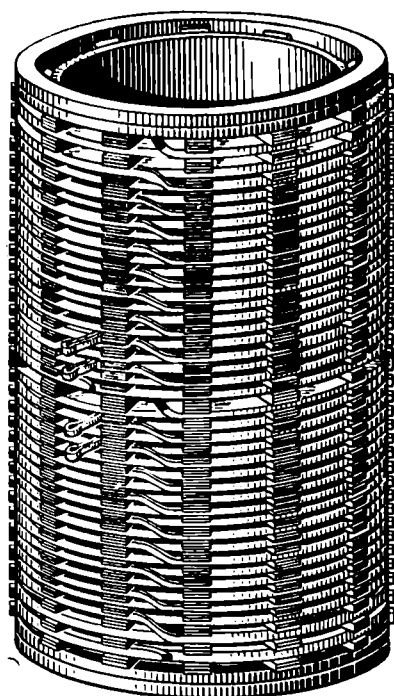


Fig. 12.13. Continuous disc HV winding with regulating taps (centre-tapped winding) and enlarged duct

the wire running from the drum is again tensioned. Owing to this, interconnection of coils is continuous without any

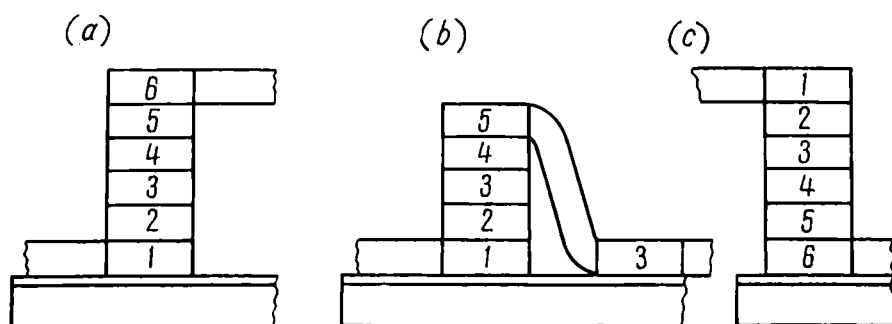


Fig. 12.14. Winding the transposition coil of continuous winding (a) initial order of winding the turns; (b) transposition; (c) order of coil turns after transposition

soldered joints. Eventually, the entire winding becomes more compact and rugged thanks to a good tensioning of the wire.

The continuous winding is wound round the battens (see Fig. 12.3 *c* and *d*) placed on the bakelite or temporary iron cylinders. The pressboard spacers, 40 or 50 mm wide, are

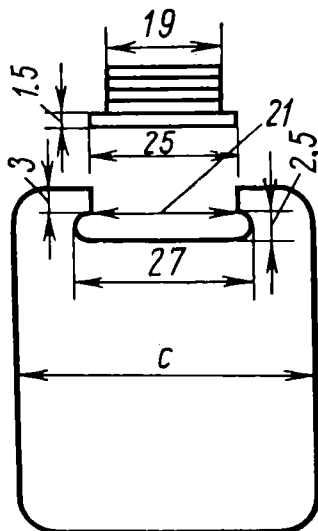


Fig. 12.15. Shapes and sizes of battens and intercoil spacers

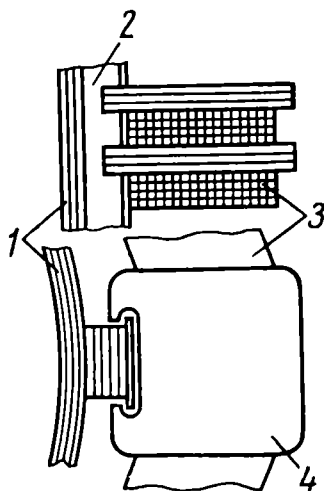


Fig. 12.16. Arrangement of battens and intercoil spacers
1—cylinder; 2—batten; 3—coil; 4—spacer

interposed between the coils so as to form the cooling ducts. These spacers are secured on the battens by means of the dove-tail connection (Fig. 12.15 and 12.16).

12.7. Helical Simplex and Duplex Windings

The helical winding resembles the layered multiplex winding inasmuch as the winding procedure is concerned.

The difference between these two is that in the layered winding the parallel conductors (making up the turn section) are laid adjacent to one another whereas in the helical winding they are placed one over another. Besides, the helical winding usually has cooling ducts arranged in between the turns. Figure 12.17 *a* and *b* shows a sectionalized portion of the helical winding.

Another feature that likens the helical winding with the continuous winding is that it is usually wound on the battens around the bakelite cylinder with insulating spacers

placed between the turns (Fig. 12.18). The helical winding is used with a relatively small number of turns and large

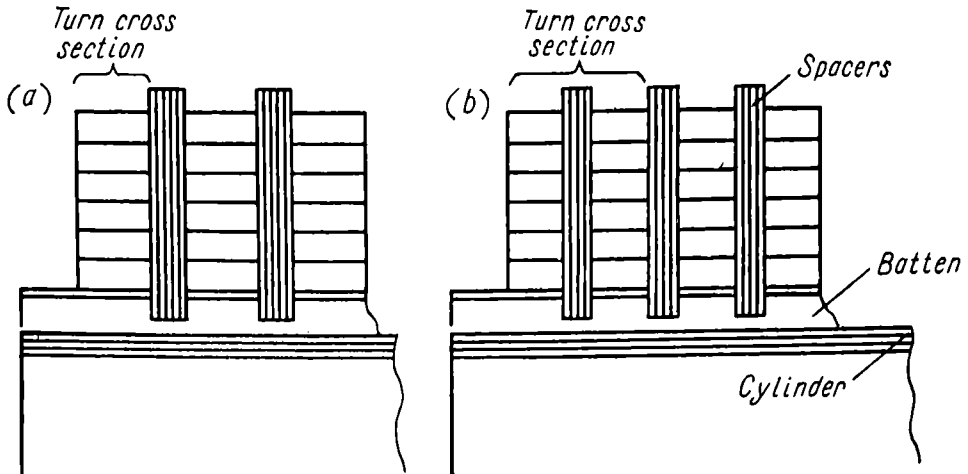


Fig. 12.17. Sectional view of helical winding
(a) simplex; (b) duplex

currents. This winding, as well as the continuous disc winding, exhibits high axial mechanical strength and finds wide application in large-size power transformers.

A distinguishing feature of the helical winding is the use of *transposed conductors* by changing the relative position of individual wires or groups of wires. The transposing is essential for equalizing the resistance and reactance of each of the parallel conductors. In the absence of the transposition these wires would be of different length and, being situated in the leakage field of nonuniform induction, would have different resistances and reactances which in turn wo-

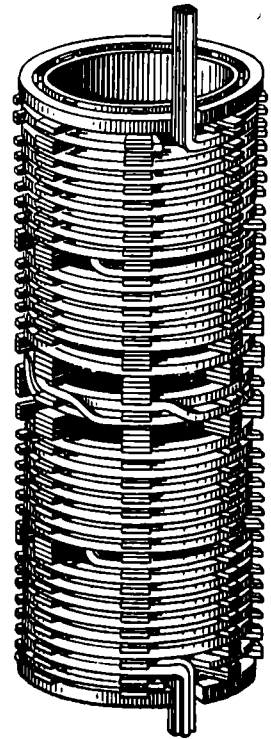


Fig. 12.18. Helical simplex winding with three transpositions

uld lead to a nonuniform distribution of current among parallel wires and overloading of some portions of the wires.

12.8. Arrangement of Transpositions in Helical Winding

Simplex winding. Transpositions in this winding are made in the following fashion. The whole of the winding length (turns) is subdivided into four equal sections. The transpositions are made between these sections, at three points of the winding. The first to be made is the so-called group transposition spaced at one fourth of the turns from the beginning of the winding. The turn in its section is divided into two similar groups of wires which are then inter-

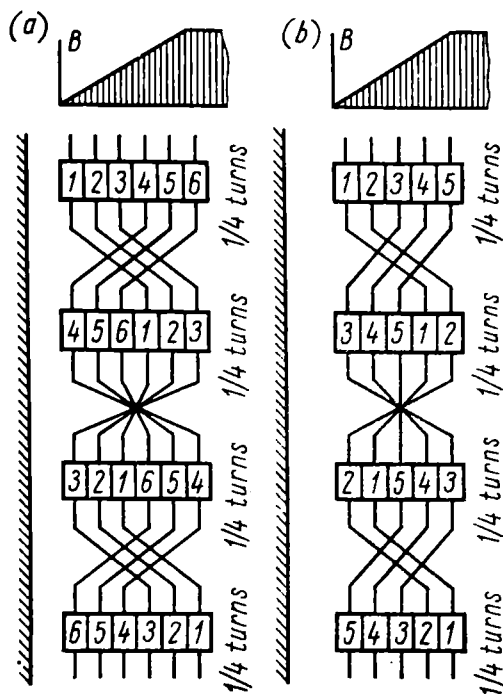


Fig. 12.19. Transposition of parallel conductors in helical simplex winding

(a) even number (6) of conductors;
(b) odd number (5) of conductors

changed, that is, the top group is placed underneath on the battens while the bottom group is lifted and laid on top.

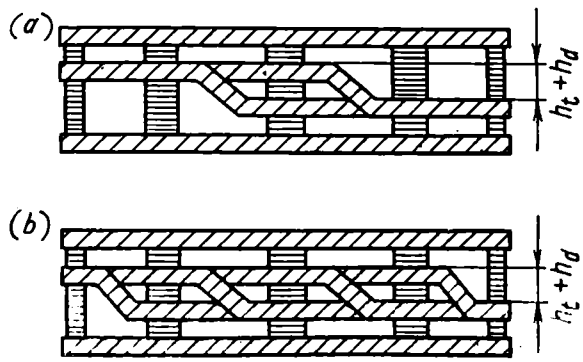


Fig. 12.20. Increase of helical simplex winding height due to transpositions

(a) group transposition; (b) common transposition of four conductors

The middle or common transposition is arranged in the middle of the winding, in which the disposition order of all the wires is fully reversed. And, finally, the group transposi-

tion is made again spaced at one fourth of the turns counting from the winding end.

The diagram showing a three-step transposition in the helical simplex winding for six and five parallel wires is given in Fig. 12.19 *a* and *b*.

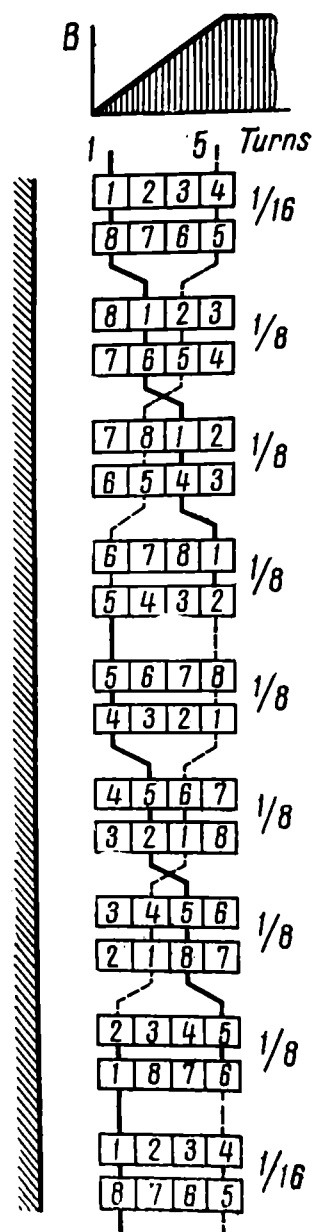
One of the ways of checking the correctness of the three-step transposition of an even quantity of wires is to see whether the sums of wire numbers for each position are equal. Thus, for example, this sum for six wires will be $1 + 4 + 3 + 6 = 14$ (see Fig. 12.19 *a*).

For practical accomplishment of the common and group transpositions, an additional axial space for one wire turn plus a duct, $h_t + h_d$, is required for each transposition (Fig. 12.20). Therefore, it is necessary to make allowances for an increased axial size of the winding by the total of three wires and three ducts when calculating its axial size.

The disadvantage of the helical simplex winding is that ampere-turns are as if thinned out at the points of transpositions, which leads to unequal distribution of magnetomotive forces throughout the height of the winding (refer to Sec. 7.1).

Helical duplex winding. In this winding a perfect transposition is obtained

Fig. 12.21. Equally distributed transposition of eight parallel conductors in helical duplex winding, 8 transpositions. Order of distribution of conductors at the start and finish of the winding is identical. Given on top of the figure is the leakage flux diagram



without losing an axial space on interchanging the wires, because the turn in its section consists of two groups of wires.

The transposition in this winding is termed uniformly distributed and is made in the following way. The entire

winding (turns) is subdivided into equal sections; the number of these sections should equal the total number of parallel wires. Then the wires are changed between these sections. The top wire of one group is placed on top of the second group while at the same time and in the same portion of the

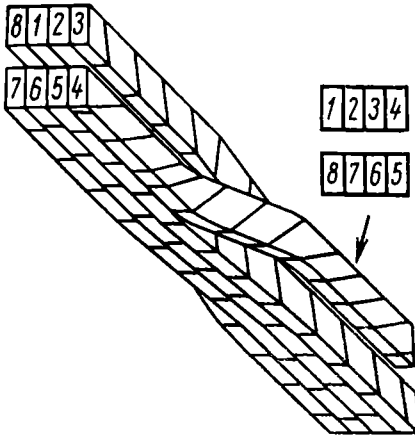


Fig. 12.22. Transposed conductors according to equally distributed transposition diagram

winding the bottom wire of the second group is inserted underneath the first group.

The procedure for making a transposition in the duplex winding is shown in Fig. 12.21. The wires are transposed in the gap between the spacers (Fig. 12.22).

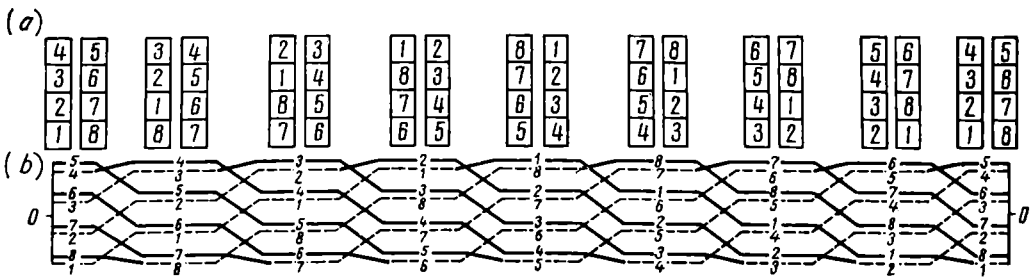


Fig. 12.23. Developed diagram of equally distributed transposition in helical duplex winding

(a) arrangement of conductors at individual winding sections; (b) developed transposition diagram (dashed line shows the conductors of the 1st branch and the solid line, those of the 2nd branch)

The proper transposition in the completed winding is normally checked by testing the wires for continuity. To make the test easier, it is better to maintain the same distribution order of wires at the start and finish of the win-

ding. To do this, it is imperative that the number of transpositions be equal to the number of parallel wires. This condition is attained by displacing half of the first section (from the winding start) to the finish of the winding.

Figure 12.23 demonstrates a developed complete diagram of the equally distributed transposition of eight parallel wires in the duplex winding.

Ultimately, we arrive at a conclusion that the first transposition should be made at a half-section length from the beginning of the winding. All subsequent transpositions are to be spaced apart at a length of one complete section. And, finally, the last transposition is again spaced within half the section length from the finish of the winding.

12.9. Examples of Calculating Equally Distributed Transposition

The spacing between transpositions,

$$l = \frac{N}{n}$$

where N = number of turns

n = number of parallel conductors

The first transposition is made at the following distance from the winding start:

$$\frac{l}{2} = \frac{N}{2n}$$

Let us consider a numerical example of determining the spacings between equally distributed transpositions.

Problem 12.1. Let $N = 42$; $n = 14$.

Solution. The length of the section is

$$l = \frac{N}{n} = \frac{42}{14} = 3 \text{ turns}$$

The first transposition should be made at a length of half the section, that is after $0.5l = 1.5$ turns from the winding start. All the subsequent transpositions will then be spaced apart at $l = 3$ turns, i.e., separated by 4.5, 7.5, etc. turns. The last transposition will be spaced from the winding start by

$$42 - 1.5 = 40.5 \text{ turns}$$

In the majority of actual cases the value l is fractional. Considering that the transpositions are made between the battens on which the helical winding is laid, the fractional part giving the value l should be expressed through the number of battens.

Problem 12.2. Let $N = 42$; $n = 12$; $n_b = 10$ (where n_b is the number of battens around the circumference).

Solution. The length of the section is

$$l = \frac{42}{12} \text{ turns} = \frac{42 \times 10}{12} = 35 \text{ battens} = 3 \frac{5}{10} \text{ turns}$$

The first transposition should be spaced from the start of the winding by

$$3 \frac{5}{10} : 2 \approx 1 \frac{7}{10} \text{ turns}$$

The result is rounded off to one tenth of the turn, i.e., to the spacing between the battens. The subsequent transpositions are to be found by consecutively adding $3\frac{5}{10}$ turns. Thus it follows that the transpositions of wires should be made within $1\frac{7}{10}$; $5\frac{2}{10}$; $8\frac{7}{10}$; $12\frac{2}{10}$...; $40\frac{2}{10}$ turns from the winding start and the total number of transpositions is 12, equalling the number of parallel conductors.

It should be pointed out that it is not desirable to cancel simple fractions because their numerators indicate the number of battens, which makes it easier for the winder to calculate the fractional part of the turn in order to make the transpositions.

Review Questions

1. Name the basic types of wire used for the transformer windings.
2. Explain the design and construction of the cylindrical layer windings, coil, continuous and helical (simplex and duplex) windings.
3. What is the purpose of transpositions in helical simplex and duplex windings and how are they made?

Chapter Thirteen

Insulation and Lightning Protection of Transformers

13.1. Level of Voltages and Overvoltages Under Service Conditions

A power transformer is intended for a long service under load. Consequently, insulation of its windings and current-carrying parts (taps, switches, etc.) are subjected to both continually applied voltages of rated industrial frequency (50 Hz) and abnormal impulse (transient) overvoltages.

Generally, *overvoltage* is an abnormal voltage much higher than the transformer service voltage and, as such, is harmful to its insulation. By overvoltage is usually meant impulse overvoltages caused by atmospheric disturbances and most severely affecting the insulation, as well as switching surges.

The switching surges may occur during routine switching operations in the power transmission lines, such as the transformer switching at no load or under load, sudden changes in the line operating conditions, etc. These surges may be three or four times the value of the phase voltage lasting only for hundredths of a fraction of a second (not exceeding, as a rule, 0.1 s). Besides, the breaks and shorts occurring in the line may give rise to breakdown overvoltages higher than the switching surges.

Lightning surges reaching a transformer under adverse circumstances may produce overvoltages ten times the phase voltage at a duration as short as a few microseconds.

The transformer insulation is classified as the external and internal. The *external insulation* refers to the insulation of windings from one another and earth while by the *internal insulation* is meant the insulation of each winding, that is its interturn, interlayer and intercoil insulation.

The normal service voltage and the switching surges affect mostly the external insulation of the windings whilst

the internal insulation suffers mainly from the lightning surges.

The reliable operation of a transformer depends upon its insulation level which characterizes the insulation with regard to its capability to withstand voltages of rated industrial frequency (50 Hz) and impulse overvoltages. The level of the transformer insulation (insulation strength) differs with a class of voltage and the kind of service the transformer is designed for. This level is selected on the basis of service experience and is specified in the appropriate standards.

Each transformer winding, depending on the applied service voltage permissible for a long time, is referred to a

Table 13.1

Rated voltages in mains, kV	Maximum service voltage, kV	Rated voltages in mains, kV	Maximum service voltage, kV
3	3.6	110	126
6	7.2	150	172
10	12	220	252
15	17.5	330	363
20	24	500	525
35	40.5		

definite voltage class expressed in terms of the rated voltage.

The ratings of the line AC voltages which are in force in the USSR are given in Table 13.1.

The rated voltage of the transformer HV winding is regarded as the voltage class of the transformer. The limits of the voltage withstand tests for the transformer winding insulation both by industrial-frequency voltage and impulse voltage are established according to different voltage classes (see Sec. 13.3).

13.2. Requirements for Insulation Strength

The correct choice of insulation gaps, adequate quality of insulating materials and construction of insulators are instrumental for a reliable service and long life of a trans-

former. On the other hand, too great margins of insulation strength are conducive to unwarrantably heavy expenditure of insulating and other materials, increase in size and total cost of the transformer.

The insulating materials must have no chemical interaction with hot transformer oil in order to keep it from fouling and decomposing.

Apart from purely electrical effects, the transformer insulation is subject to heating due to copper and core losses and to mechanical stresses which may be substantial in case of shorting. All those factors should be accounted for when designing a rational model.

It is commonly assumed that a properly designed transformer operating under normal conditions should serve at least 15 to 20 years and this durability much depends on the fact whether the basic properties of the transformer insulation are preserved throughout its service life.

Proper technological treatment of insulation is vital for obtaining adequate insulation strength. One of the most essential operations in this respect is the vacuum drying of the transformer active components after assembly and before oil filling.

The minimum contact surface between oil and air is a desirable asset of any oil-cooled transformer and, therefore, it is good practice to use hermetically-sealed oil conservators, chemical dehumidifiers, etc.

13.3. Insulation Tests and Test Voltages

The insulation strength of transformers is tested by 50-cycle voltage and impulse voltage.

Each manufactured transformer is subjected to acceptance trials which always include a 50-cycle test. The latter test is performed mostly in two ways: (a) by applying voltage from an external source, with the transformer core de-energized and (b) by energizing the transformer with induced voltage.

The applied-potential test diagram is shown in Fig. 13.1. The test voltage V_{test} is applied to the winding tested and earthed parts. The remaining windings should also be earthed. The test is usually started with the LV winding. In this case external insulation is tested, that is the insulation of

all windings and leads from the earthed parts and from other windings.

The specified values of 50-cycle test voltages are given in Table 13.2 as functions of voltage classes, i.e., the rated values of service voltages.

When subjected to an induced-potential test, the transformer is fed with an increased (usually twice the rated value)

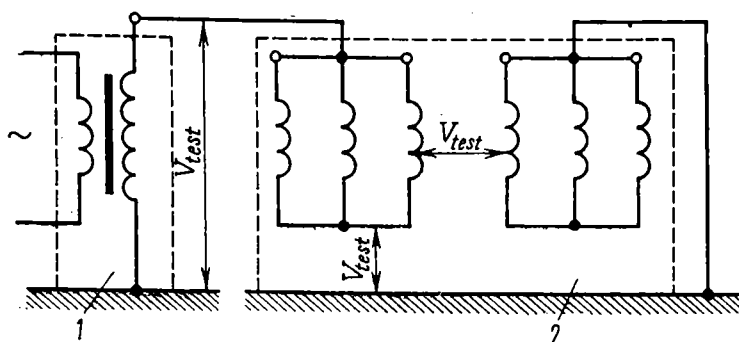


Fig. 13.1. Schematic diagram incorporating test transformer for testing the external insulation of three-phase transformer with applied voltage of industrial (50 Hz) frequency
1—test transformer; 2—transformer tested

voltage. In view of the fact that this test leads to a density rise of the main magnetic flux proportional to voltage, the induction is decreased by increasing the frequency (to 100-

Table 13.2

Voltage class, kV	Test voltages		
	applied effective voltage, kV	impulse peak-to-peak voltage, kV	
		full wave	chopped wave
3	18	44	50
6	25	60	70
10	35	80	90
15	45	108	120
20	55	130	150
35	85	200	225
110	200	480	550
150	275	660	760
220	400	950	1090
330	460	1050	1150
500	680	1550	1650

250 Hz), obviating thereby the inrush of the magnetizing current dangerous to the feed winding. The induced-potential test is used for testing internal insulation, i.e., inter-turn, interlayer and intercoil insulation.

Occasionally, one of the ends of the HV winding of the single-phase transformer or the neutral point of the HV winding of the three-phase transformer intended for connection to earth (in the earthed-neutral systems) has a reduced insulation resistance to earth. These windings should not

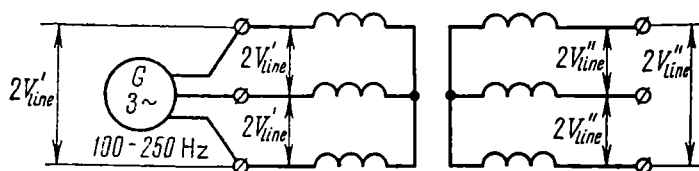


Fig. 13.2. Testing the internal insulation of three-phase transformer with increased (double the rated value) voltage induced in transformer tested at increased frequency (100 to 250 Hz). V'_{line} and V''_{line} = rated line voltage

be given an applied-potential test but should be tested only with an induced voltage. In this case a potential equal to the applied test voltage, corresponding to the given voltage class (Table 13.2), should be impressed across the line end of such a winding.

The induced-potential test diagram is shown in Fig. 13.2.

New transformer models and their insulation assemblies are tested by gradually increasing the test voltage to the specified limit. Often the test is continued until a complete breakdown of insulation occurs. In this way we can determine the electric strength margin of a transformer which is given by

$$K_{s. m} = \frac{\text{Breakdown voltage}}{\text{Test voltage}}$$

To obtain a reliable insulation level, a definite margin of electric strength is necessary due to inevitable scatter of the test results.

Inasmuch as impulse voltage tests are fairly complicated and expensive, they are conducted only with a view of checking new designs of insulators. These tests are commonly run on test specimens or experimental models and are repeated whenever required.

The values of the impulse test voltages are given in Table 13.2 above. As is apparent from this Table, the amplitude of the impulse voltages is appreciably higher than the values of 50-cycle test voltages. This is attributable to the nature of impulse overvoltages. To compare the two, the values of 50 Hz voltages should be multiplied by $\sqrt{2}$.

13.4. Effect of Flashover Voltages on Insulation

The transformers associated with overhead transmission lines suffer mostly from lightning surges. These are mainly large HV transformers and transformers of smaller sizes rated at 10 and 35 kV.

The effect of flashover voltages on insulation is determined both by their peak amplitude and waveform, i.e., vari-

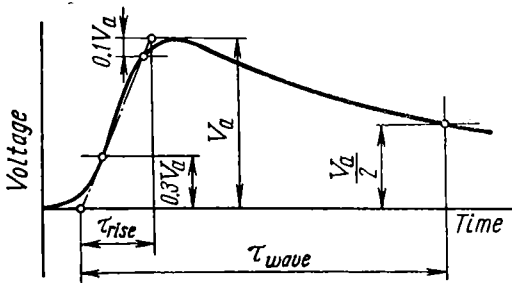


Fig. 13.3. Typical full impulse wave (1.5/40 μ s)

ation of the impulse wave in time and its total duration.

The effect of the impulse wave, apart from its amplitude, is also greatly dependent on the steepness of its wave-front, i.e., the pulse rise time (the steeper the front, the stronger the wave effect). That is why the given duration of the wave-front should be strictly maintained within the specified limits during impulse voltage withstand tests.

The waveforms of the lightning surge impulses are exceedingly diverse. However only two typical waveforms, as most frequently encountered in practice, are chosen for the impulse voltage withstand tests. These are the full- and chopped-wave impulses.

The full waveform is given in Fig. 13.3 where $\tau_{rise} = 1.5 \pm 0.2 \mu$ s is the rise time; $\tau_{wave} = 40 \pm 4 \mu$ s is the total wave length; V_a is the impulse amplitude.

The chopping of the wave occurs, for example, on suspension insulators, leads, etc. The chopped wave is dangerous to the internal insulation of a winding because of its large peak-to-peak amplitude V . The form of the chopped impulse wave is shown in Fig. 13.4.

Development of electrically strong insulation capable of withstanding impulse effects by merely enlarging the insulating gaps would necessitate a substantial increase in the transformer standard power and, consequently, would be too

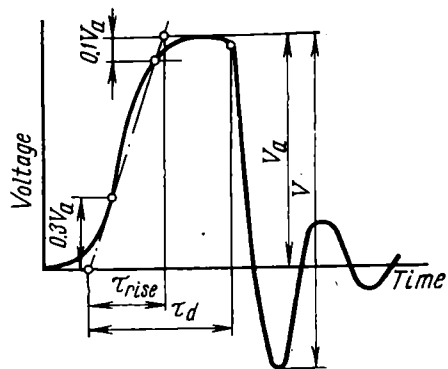


Fig. 13.4. Typical chopped impulse wave $\tau_d = 2$ to $3 \mu s$ (pre-discharge time)

costly. All this poses a problem of devising the most rational insulation which could possess sufficient electric strength without appreciable increase of the size of a transformer. To solve this problem, it is essential to elucidate the phenomena occurring in the winding whenever the surge voltage wave impinges on it. The experiments show that these phenomena are fairly complicated. In the simplified form the phenomena in question may be reduced to the following. Suppose a steep-fronted impulse wave has reached the line input terminal of an HV winding. Experience shows that safety of a transformer depends to a great extent on how uniformly the impulse amplitude is distributed in the internal insulation of the winding. The more uniform the voltage distribution (potential gradient) in the winding, the greater the insulation strength, because in this case the insulation becomes equistrong.

In the continuous disc windings, commonly employed in large transformers, the potential gradient is not uniform at the initial instant of the incidence of the impulse wave,

which makes it fairly difficult to render the insulation resistant to impulse voltage effects.

Since the wave-front is very steep, it can be diagrammatically represented as a part of the high-frequency voltage sine-wave (Fig. 13.5).

With rapid changes in voltage at high frequencies, the initial potential-gradient is largely determined by the capacitances present in the windings. As far as the inductances

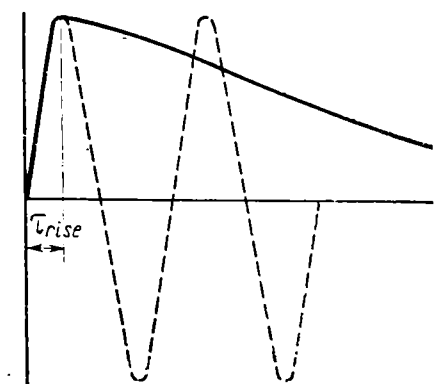


Fig. 13.5. Steep wave-front shown as part of high frequency sine-wave

of the winding coils are concerned, they cannot affect the initial potential-gradient because of a high rise of inductive reactance at high frequency ($X = \omega L$). Considering the above conditions, each disc winding may be represented for simplicity as a capacitor plate with capacitance C_e connected to earth and capacitance C_c connected to the adjacent coil in the equivalent diagram of the HV continuous winding of a modern large transformer. Actually, the coil proper has inherent capacitances and therefore its representation through a capacitor plate can be taken as an assumption.

The LV winding may be considered practically earthed because of its proximity to the core leg and its comparatively large capacitance to earth (Fig. 13.6b).

Thus, at the initial instant of the impulse wave effect the equivalent diagram of the HV winding will take the form of a capacitive network (Fig. 13.6b). This diagram refers to the case of an earthed-neutral circuit commonly used in the USSR for the power supplies of 110 kV and above.

To simplify the reasoning, let us assume that all the coils are identical. Then the intercoil capacitances C_c as well as the coil capacitances to earth, C_e , will be equal. We shall

begin with the last coil at the earthed end X. Supposing that a current I flows through the last (on the diagram, bottom) capacitor C_e . Then, the current through the penultimate capacitor will be $I + I_1$, where I_1 is the current branched off into the last C_e capacitor. In the next (third from below) capacitor C_c the current will now be $I + I_1 + I_2$, where I_2 is the current through the penultimate capacitor C_e . It should be stressed here that $I_1 < I_2 < I_3$ and so on, because

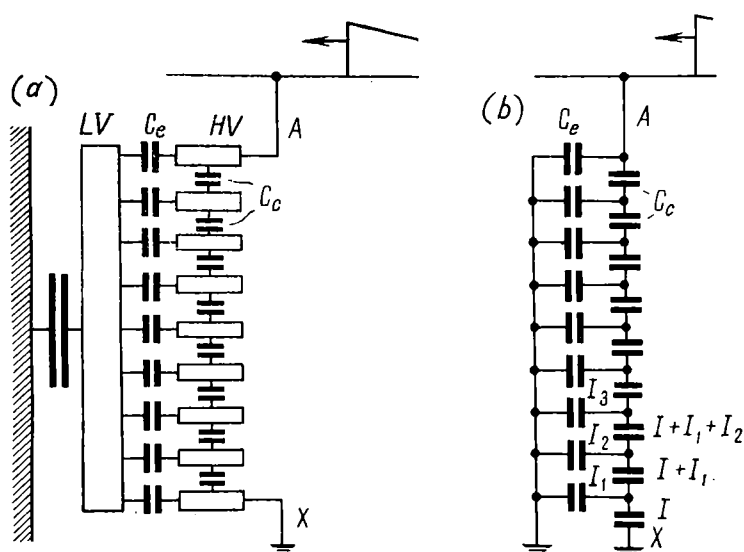


Fig. 13.6. Equivalent diagram of HV continuous winding

the voltage across the upper capacitors is higher. Reasoning as above, we shall eventually find that the intercoil currents will rise as they flow upwards. Consequently, the largest current will flow through the topmost capacitor C_c .

In view of the fact that capacitive resistances between the coils are equal, we shall obtain on the basis of Ohm's law that the voltage drop across any coil will be the greater, the higher this coil is situated. This results in a nonuniform potential gradient throughout the height of the winding. This is the reason why the coils situated closer to the line input (the so-called input coils) should be better insulated because they have to withstand a higher voltage.

Let us construct a chart of initial gradient through the winding for an ideal wave, i.e., at $t_f = 0$. We plot the wave

amplitude V_a on the ordinate axis and the total height of the winding on the abscissa axis (Fig. 13.7).

If the potential gradient were uniform (an ideal case) the chart would be represented through a straight line BX . But actually the voltage will follow a certain curve known as the *initial gradient curve* because of the above-discussed distribution of currents through the capacitance network. This curve pictorially shows that the upper coils suffer

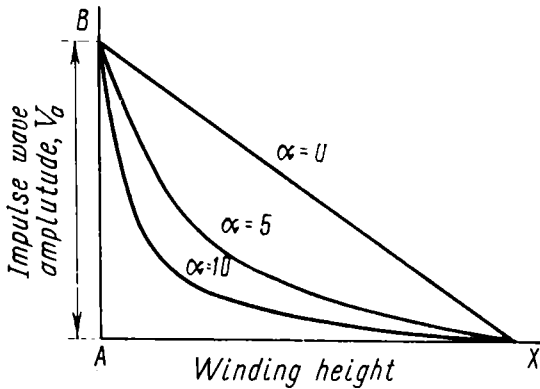


Fig. 13.7. Initial potential-gradient chart

most from impulse effects than would be the case with a uniform gradient. The extent of this nonuniformity is associated with a gradient factor

$$\alpha = \sqrt{\frac{C_e}{C_c}}$$

The smaller is the α , the more is the approximation of the curve to the finite gradient straight line ($\alpha = 0$); ordinarily, $\alpha = 5$ to 15.

The great danger presented by overvoltages which cause damage to the transformer windings necessitated the use of special protection, the so-called surge diverters or lightning arresters.

The lightning protection of the transformers is mainly devised on the basis of experimental data derived from measurement tests of models and similar constructions, impulse tests, etc. The capacitance network is hard to calculate because of inaccuracies in determining capacitances C_p , C_c and inductance L . The calculations are still more complicated due to nonuniform distribution of the winding turns and

coils. Therefore, all these calculations should be regarded as approximate, and need practical verification.

The protection of transformers against overvoltages may be external and internal.

The external protection includes:

(1) installation of various kinds of lightning arresters limiting the surge voltage amplitude on the line;

(2) suspension of earthed lightning protective cables over the overhead wires. These cables receive direct lightning strokes and help to attenuate the impulse wave-front near the transformer.

However, the external protection alone is insufficient since the amplitude of the impulse waves not arrested by the external devices is still fairly high. Therefore, in addition, internal protection means should be incorporated in a transformer. The internal protection is based on two main principles: increase in the insulation strength of the input coils and artificial reduction in the nonuniformity of the initial potential gradient. The simplest of the two is the increase in the insulation strength of the input turns and coils which suffer most from the impulse effects. Unfortunately, this kind of protection alone in the transformers which are in serial production in the USSR is good only for voltages up to 35 kV. At higher voltages, 110 kV and more, the transformer size has to be substantially increased on account of the above reasons and also due to the resultant nonuniform distribution of the ampere-turns throughout the height of the winding (in the input coil zone), which makes this method ineffective.

The second principle of devising the internal protection, referred to as a *capacitive shielding* or *capacitive neutralization*, will be more appropriate although it is more sophisticated. This method involves neutralization of stray coil capacitances C_e to earth, thereby minimizing the nonuniformity of the initial potential gradient.

A transformer with capacitive neutralization has the potential gradients per each coil distributed more or less uniformly throughout the winding height, which greatly improves the insulation level. Such transformers are also called *non-resonating* because the transient oscillations are nearly or fully absent from the initial to final gradients.

In the past years, a lap winding has been brought into wide use for HV windings rated at 110 kV and above. The turns of this winding are interlaced in each twin coil, which greatly increases the longitudinal capacitance of the winding and equalizes the initial potential gradient.

13.5. Protection of Power Transformers Rated up to 35 kV

For voltage classes not exceeding 10 kV no additional measures for increasing the insulation strength are required on account of sufficient electric strength margin. It is only in the case of layer windings that a screen connected to the line input is used (see below). For voltages of 35 kV, it is sufficient to increase the thickness of the conductor insulation of two input coils (use of a conductor with insulation thickness of 1.35 mm on both sides). The width of each of the two extreme oil ducts between the coils should be at least 6 mm.

13.6 Capacitive Neutralization of Transformers Rated at 110 kV and Above

The basic principle of the protection of transformers rated at 110 kV and more involves the arrangement of an additional capacitance network connected to the line input terminal from the outside of the winding.

Extension of this network to the end of the winding gives a balanced circuit in which additional capacitances C_{ad} neutralize the stray capacitances C_e (Fig. 13.8). This enables the currents to be distributed in the capacitors so that the initial potential gradient may be uniform (in an ideal case).

However, the circuit like this is inapplicable in practice because the lowest capacitor C_{ad} is found to be at full impulse voltage, which requires a considerable increase of the capacitor size. Nevertheless, this principle is utilized as the basis for a majority of the capacitive protection circuits.

In view of the fact that full capacitive neutralization is hard to devise, use is made of partial neutralization which

is adequate to bring the initial gradient curve sufficiently close to the final gradient curve (Fig. 13.9).

It should be pointed out, though, that a perfectly uniform initial potential gradient is practically not required. The idea is to prevent the gradient in the high-tension points of

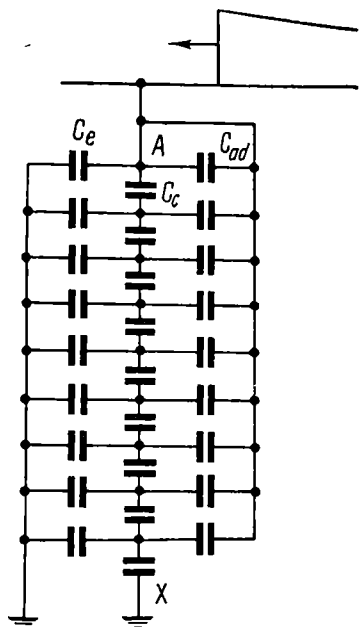


Fig. 13.8. Capacitive neutralization principle

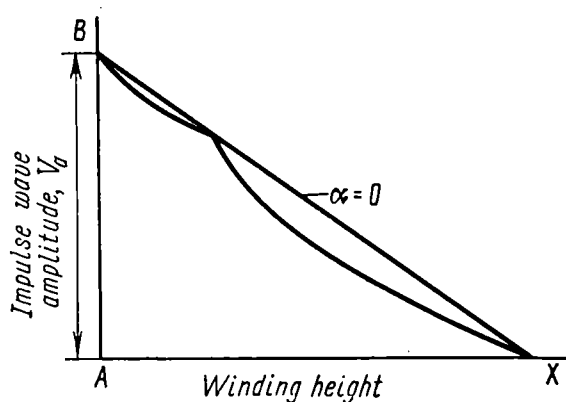


Fig. 13.9. Initial gradient curve for partial neutralization

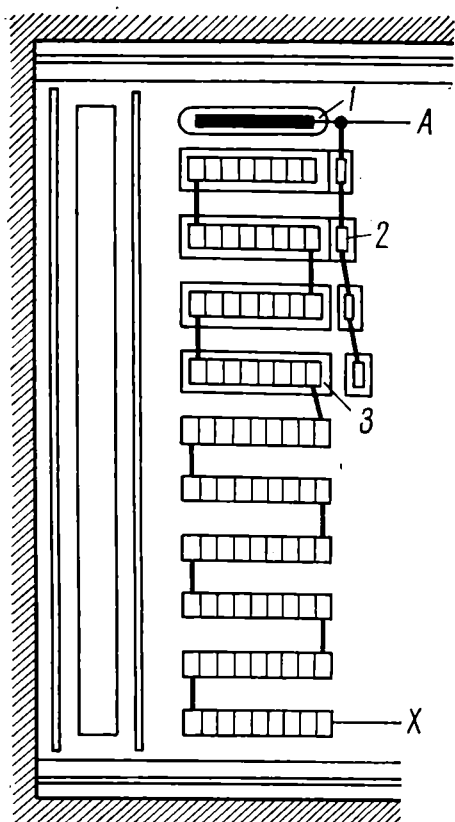
the winding from rising considerably above those average gradient values that would prevail in the case of uniform voltage gradient.

The partial protection of a transformer by means of screening turns involves the following procedure. The screening turns are superposed on the six terminal coils (for 110 to 220 kV) at a various distance from one another. These turns, made from a well-insulated wire, are then interconnected and coupled to the line input (Fig. 13.10).

Capacitive ring 1 placed over the winding to equalize the voltages across the turns of the input coil (Fig. 13.11) is actually a ring (or collar) of pressboard wrapped with copper or aluminium foil and securely insulated.

The capacitive ring is connected to the line input of the winding.

The screening turns do not enter the spacing between the phases *A*, *B*, *C*, that is, they do not surround completely the winding coils (Fig. 13.12).



The partial protection of a transformer with screening turns is advantageous in that:

(a) it is simple to construct and produce;

(b) it permits the increased (to a certain level) protection by adding the screening turns without changing the winding design;

(c) it affords precalculation of capacitance.

Fig. 13.10. Partial protection with screening turns

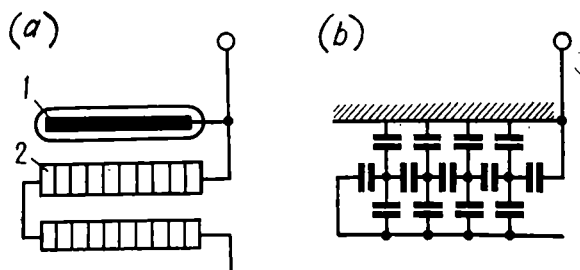
1—capacitive protection ring; 2—screening (capacitive) turns; 3—coils with reinforced (added) insulation

The following are the disadvantages of this kind of protection:

(a) limited range of equalization;

Fig. 13.11. Capacitive protection ring

(a) structural arrangement; (b) equivalent capacitive circuit diagram; 1—capacitive ring; 2—extreme (input) winding coil

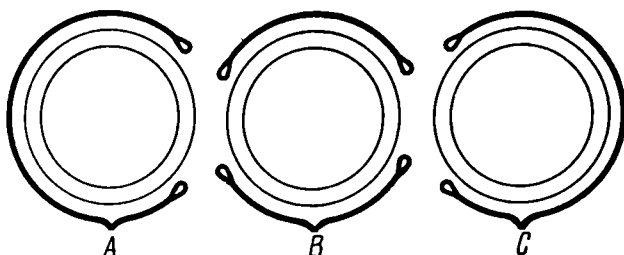


(b) high voltage between the last screening turn and the winding. This linear voltage may come to 40 per cent of the wave impulse amplitude;

(c) inapplicability for inner windings;

(d) incomplete protection coverage of coils, which leads to a weaker protection of the mid phase of a three-phase transformer.

Fig. 13.12. Arrangement of screening turns on HV windings of three-phase transformer. Input coils are not completely surrounded with screening turns



13.7. Internal Capacitive Equalization of Inner Windings

This protection involves the use of two capacitive screens between each pair of coils, artificially increasing thereby intercoil capacitance C_c and decreasing the gradient factor α . Figure 13.13 gives an idea of this kind of protection.

Let α_1 denote the gradient factor obtained after equalization. Then,

$$\alpha_1 = \sqrt{\frac{C_e}{C_c + C_{c1}}} < \alpha = \sqrt{\frac{C_e}{C_c}}$$

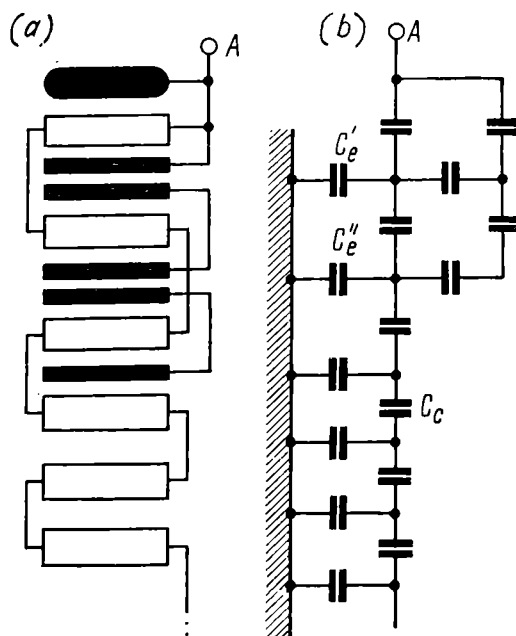


Fig. 13.13. Diagram showing partial capacitive neutralization of continuous winding by means of built-in capacitors

(a) structural arrangement; (b) simplified equivalent diagram

where C_{c1} is the additional intercoil capacitance obtained by means of capacitive screens.

This kind of protection yields a flatter curve of the initial potential gradient (Fig. 13.14).

The advantage of the longitudinal capacitive equalization is that it can be extended throughout the height of the

winding; the disadvantage is a great loss of space in the axial direction of the winding.

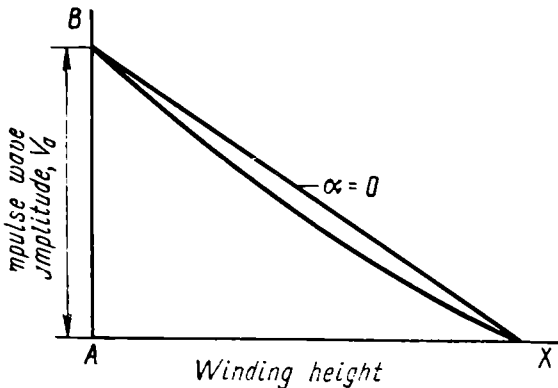


Fig. 13.14. Initial gradient curve of internal insulation protection

There are at present a number of other kinds of partial protection, all possessing their specific advantages and disadvantages.

13.8. Layer Windings

The layer windings are used for relatively small transformers rated up to 35 kV.

In spite of some of its weaknesses, the layer winding is simple in construction and has a valuable advantage of ensuring a practically uniform initial potential-gradient with no additional capacitive neutralization employed (apart from the capacitive screen). In other words, the layer winding is lightning-proof in principle, i.e., has inherent lightning protection because its gradient factor is nearly zero. The equivalent circuit diagram and the

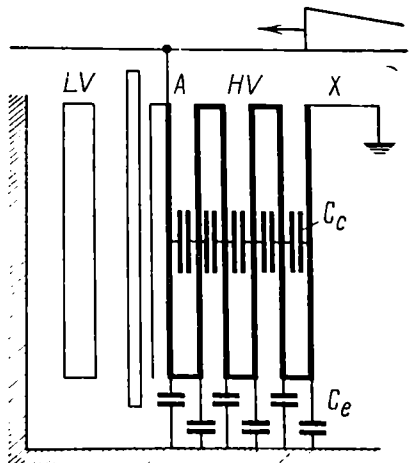


Fig. 13.15. Equivalent diagram of layer winding

initial gradient chart are shown in Fig. 13.15 and Fig. 13.16.

As is apparent from the diagram, a layer of this winding acts at the instant the impulse wave arrives as a capa-

citor plate. In this case the interlayer capacitance corresponds to capacitance C_c as is clear from the equivalent diagram. As each layer's capacitance to earth is fairly small with respect to the interlayer capacitance C_c , the initial gradient factor α is close to zero, i.e.,

$$\alpha = \sqrt{\frac{C_e}{C_c}} \approx 0$$

The initial gradient curve will be almost coincident with the straight line of the final gradient. This curve is repre-

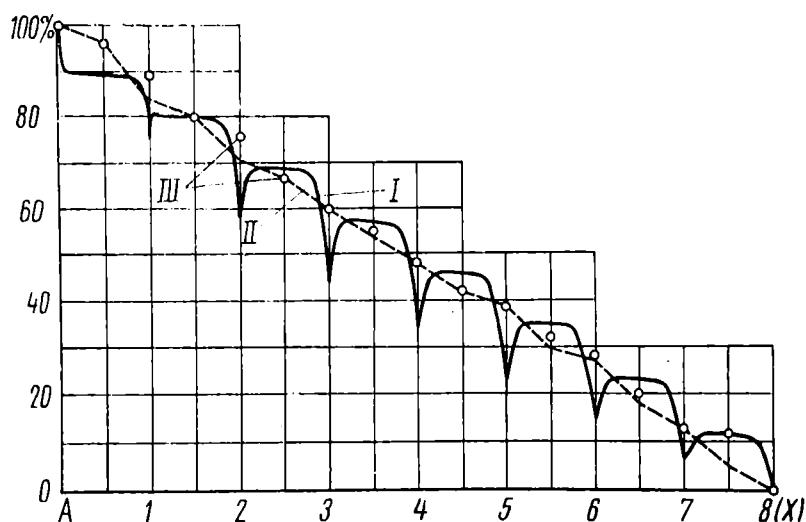


Fig. 13.16. Potential gradients in HV layer winding with two screens
I—capacitance gradient; II—initial gradient at full wave; III—peaks of potentials at full wave

sented on the chart in the form of a broken line where the number of knee points will correspond to the number of layers.

To equalize the voltages across the turns of the first (input) layer, a split metallic screen is connected to the line input terminal.

The advantages of the layer winding will be exploited to the full if this screen is placed inside, facing the first layer. This helps to decrease the total capacitance of the winding to earth.

The limitations in the application of the layer winding mainly arise from its inadequate and small cooling surface

and high tension between the layers. To circumvent the latter disadvantage, the winding is subdivided into two or more axial parts, making it a coil winding.

13.9. Choice of Correct Size of External and Internal Insulation of Power Transformer

The desired insulation strength is attained by correct choice of insulation materials, appropriate insulation structures, and minimum-permissible insulation gaps (spacings) between the current-carrying parts or between the current-carrying and earthed parts depending on the rated voltage of a winding. The transformer insulation chosen is intended to guard the current-carrying parts, like the windings, taps,

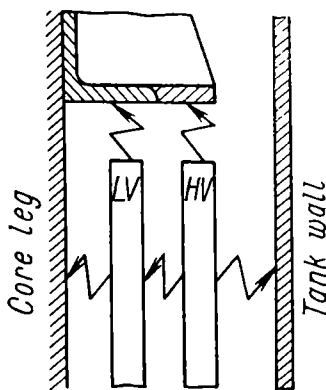


Fig. 13.17. Main insulation gaps of external insulation in concentric windings

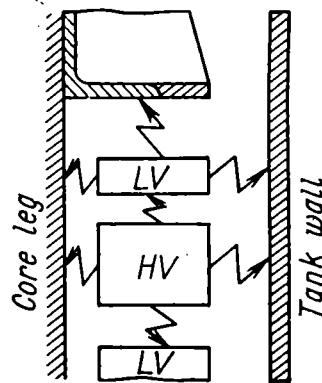


Fig. 13.18. Main insulation gaps of external insulation in sandwich windings

switches, leads, etc., against a short circuit to earth or a short circuit between the parts both at the normal service voltage and in the case of possible overvoltages.

Transformer insulation should withstand the standardized test voltages applied during acceptance and type tests of a transformer. These test voltages are listed above in Table 13.2. Insulation of each current-carrying part is designed on the basis of these test voltages with the aim to determine the main insulation gaps between the current-carrying part in question and either the earthed or the next current-carrying part.

The arrangement of insulation gaps is governed by the transformer construction, i.e., the mutual position of the windings, core, tank and other parts.

The main versions of the insulation structures used for concentric and sandwich windings, which have become classical in a way, were selected in the process of development of the transformer industry. Thus, the main insulation gaps of external insulation of a core-type transformer (Fig. 13.17) are the duct between the LV winding and the core, the duct between the HV and LV windings, the gap between the HV winding and the tank wall, between the HV windings of different phases (interphase spacings) and between the end faces of the LV and HV windings and the yoke.

As far as the sandwich disc windings are concerned (Fig. 13.18), the main gaps of external insulation are: between the coils of the HV and LV windings, between the coils and the core leg, coils and the tank wall, between the adjacent phase coils, and between extreme coils of the LV winding and the yoke.

Table 13.3

Transformer kVA rating	LV winding test voltage, kV	Spacing between LV winding end face and yoke, $h_{y-wdg 1}$, mm	LV winding, spacings from core leg, mm			
			$b_{wdg 1}$	$a_{ins 1}$	$a_{wdg 1}$	$h_{ins 1}$
25-250	5	15	2×0.5	—	4	—
400-630	5	**	2×0.5	—	5	—
400-630*	5	**	4	6	15	18
1000-2500	5	**	4	6	15	18
630-1600	18, 25 and 35	**	4	6	15	25
2500-6300	18, 25 and 35	**	4	8	17.5	25
630 and more	45	**	5	10	20	30
630 and more	55	**	5	13	23	45
All ratings	85	**	6	19	30	70

* Data given for helical winding with test voltage of 5 kV.

** Spacing of LV winding from yoke is taken as $h_{y-wdg 2}$, i. e., equal to spacing of HV winding from yoke as given in Table 13.4.

In the transformer constructions now in use, the insulation gap may be filled either with oil or hard matter (press-board, cable paper) or combination of these (Fig. 13.19).

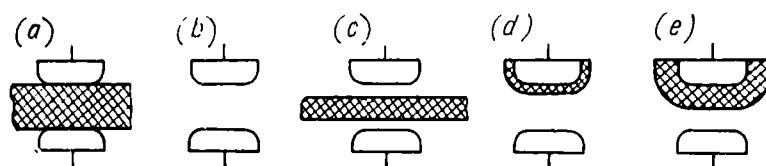


Fig. 13.19. Filling the insulation gaps

(a) hard-body dielectric insulation; (b) oil-filled gap; (c) barrier; (d) coating one of electrodes; (e) insulating one of electrodes

The material used for filling the gap determines its minimum-permissible size for a given test voltage.

The positions of the main insulation gaps for transformers designed to withstand test voltages of up to 85 kV is shown in Fig. 13.20.

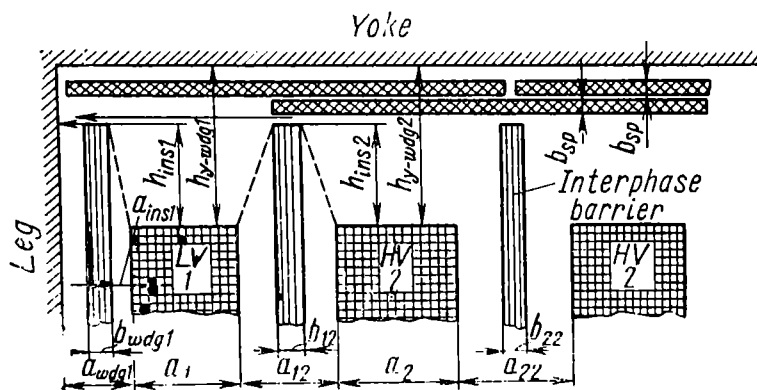


Fig. 13.20. Insulation gaps of external insulation in HV and LV windings for test voltages of 5 to 85 kV. Dashed lines show discharge paths which determine sizes L_{ins}

The minimum gaps of external insulation for oil-filled power transformers are given in Table 13.3 for an LV winding and in Table 13.4 for an HV winding.

Figure 13.21 illustrates the location and minimum sizes of gaps of external insulation for power transformers tested at 200 kV (all sizes are in mm).

The electric strength of the internal insulation is ensured by the appropriate choice of the interturn, interlayer and intercoil insulation.

Insulation of the winding conductor serves as the interturn insulation. The added thickness of the interturn insu-

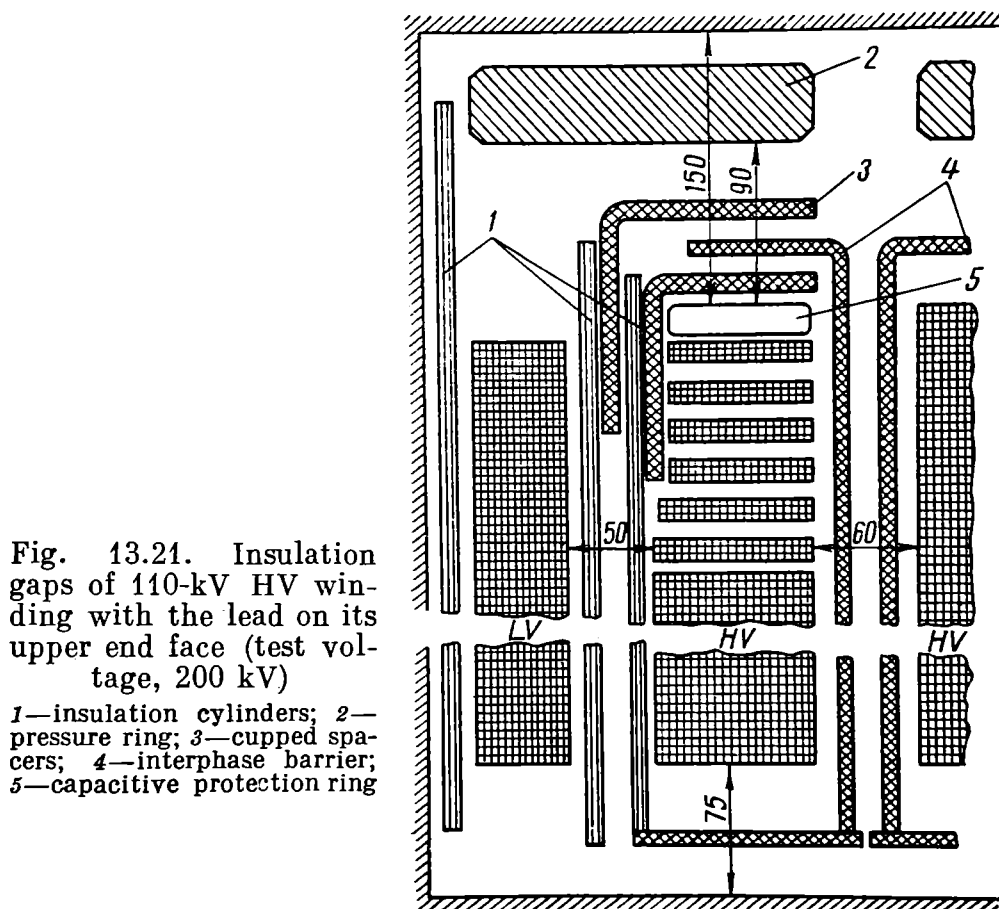


Fig. 13.21. Insulation gaps of 110-kV HV winding with the lead on its upper end face (test voltage, 200 kV)

1—insulation cylinders; 2—pressure ring; 3—cupped spacers; 4—interphase barrier; 5—capacitive protection ring

lation is used for input coils tested at 55 kV and more. The thickness of the conductor insulation is given in Table 13.5.

The interlayer insulation of the cylindrical multilayer windings made of round conductor is effected with cable paper, grade K-12, 0.12 mm thick. The number of paper layers between the two layers of turns is found from the total working voltage across the two layers of the winding (Table 13.6). The height of the interlayer insulation is made greater than the height of the layer of turns in order to increase the creepage distance. This accounts for a certain protrusi-

Table 13.4

Transformer kVA rating	HV winding test voltage, kV	HV winding spacing from yoke, mm		Spacing between HV and LV windings, mm		Cylinder protrusion, h_{ins2} , mm	Spacings between HV windings	
		h_{y-wdg2}	b_{sp}	a_{12}	b_{12}		a_{23}	b_{22}
25-100	18, 25 and 35	20	—	9	2.5	10	8	—
160-630	18, 25 and 35	30	—	9	3	15	10	—
1000-6300	18, 25 and 35	50	—	20	4	20	18	—
630 and more	45	50	2	20	4	20	18	2
630 and more	55	50	2	20	5	30	20	3
160-630	85	75	2	27 *	5	50	20	3
1000-6300	85	75	2	27	5	50	30	3
10,000 and more	85	80	3	30	6	50	30	3

* Minimum insulation gap between LV winding and electrostatic screen of cylindrical layer HV winding is 27 mm; thickness of screen with insulation is 3 mm.

a_1 and a_2 are radial sizes of correspondingly LV and HV windings in mm.

Table 13.5

Winding test voltage, kV	Conductor insulation type and cross-section shape	Conductor insulation thickness, double size, mm	Application
5 to 85	Enamel with cotton-paper covering, round	0.125-0.21 (0.14-0.3)	All transformers
	Cable or telephone paper, round	0.3 (0.035), normal	Same as above
	Cable or telephone paper, rectangular	0.45 (0.54-0.59), normal; 0.96(1.06), added	Same as above
200	Cable or telephone paper, rectangular	0.96 (1.06)	In transformers incorporating capacitive shielding (lightning-proof design)
		1.35 (1.5), added	
		1.92 (2.07) 2.96 (3.11) 4.4 (4.65). added	In transformers without lightning protection

Note: Enclosed in brackets are estimated sizes including the tolerances.

on of the interlayer insulation from the end faces of the winding.

The cable-paper interlayer insulation thickness in the multilayer cylindrical winding made of rectangular conductor may also be taken from Table 13.6 on the basis of the cable-paper thickness.

Table 13.6

Total working voltage across two winding layers, V	Total cable paper insulation thickness, mm	Height of interlayer insulation on end faces of winding (on one side of layer), mm
Up to 1000	2×0.12	10
1000-2000	3×0.12	16
2000-3000	4×0.12	16
3000-3500	5×0.12	16
3500-4000	6×0.12	22
4000-4500	7×0.12	22
4500-5000	8×0.12	22
5000-5500	9×0.12	22

In the case of a two-layer rectangular-conductor cylindrical winding used in the oil-filled transformers, the interlayer insulation with a total working voltage of not more than 1 kV across the two layers is provided by an axial oil-cooling duct not less than 5 mm wide or by a spacer composed of 1 or 2 layers of pressboard 0.5 mm thick.

The intercoil insulation in the continuous disc winding is provided by radial oil ducts. For power capacity of up to 1000 kVA and service voltage of 35 kV, the oil ducts should alternate with pressboard spacers. The spacer should protrude beyond the external surface of the coil at least by 6 mm. The spacer thickness is 2×0.5 mm.

The axial size of the oil duct (rounded off to 0.5 mm) is

$$h_{duct} = \frac{6V_{coil}}{1000}, \text{ mm}$$

where V_{coil} is the working voltage of one coil, V.

The duct size should be no less than 4 mm and should be checked for heat dissipation against Table 10.2.

The ducts at the points of break in the middle of the HV winding (at the tap points) are enlarged in contrast with the rest of the ducts. The enlarged sizes of the ducts are determined on the basis of a maximum possible voltage across the break (with the tapping switch set to the minimum voltage step).

In the windings of the voltage class of 20 and 35 kV, two extreme top and bottom ducts between the coils should be at least 6 mm each. In the case of 110 kV, five extreme ducts located at the line terminal should be 10 mm each.

The input coils of the windings rated at the voltage class of 110 kV should have common coil insulation made from cable paper 3 mm thick for the first coil and 1.5 mm thick for the second coil on both sides.

Review Questions

1. Give the definition of overvoltage.
2. What causes overvoltages in the power-transmission lines?
3. Describe the procedure of acceptance tests for the insulation strength of a transformer.
4. What is the external and internal insulation of a transformer?
5. How is the margin of safety of insulation determined?
6. Why do internal capacitances of the winding play a dominant role in the distribution of voltage through the winding at the instant of incidence of the impulse wave on a transformer?
7. Why do extreme turns and coils require added insulation?
8. What are the construction and purpose of capacitive rings and screening turns?
9. Why is the layer winding inherently lightning-proof?

Chapter Fourteen

Design of Transformers

14.1. General Considerations

The process of designing power transformers encompasses a variety of engineering problems. A transformer structure is developed on the basis of electromagnetic, thermal and mechanical calculations made to ensure desired electrical and service parameters. Such problems as the required electric strength, mechanical ruggedness, dynamic and thermal resistance of windings in the event of a short-circuit are solved at the stage of design. Essentially, a transformer should be so designed as to give a reliable service.

When designing a transformer, much emphasis should be placed on lowering the transformer cost by saving the materials and reducing to a minimum labour-consuming operations in its manufacture.

To meet the above requirements, the designer should be well familiar with the amount of labour consumed in production of the transformer parts and assemblies and with the prices of basic materials.

The process of design is closely related to that of production. It is often the case that joint efforts of designers and engineers are needed, especially in the development of new models when it is necessary to clarify the problems regarding the requisite associated equipment. The usefulness of the new design and construction practices introduced by designers and engineers should be checked on experimental models.

The problems of improvement of the models already in use and creation of the new types are closely associated with the theory of transformer design, high voltage equipment

technology, properties of magnetic and conducting materials, study and utilization of theoretical and experimental research data essential for further development of transformers. It is of paramount importance that designers and engineers keep abreast of the modern trends and practices in the transformer industry.

Equally important for the development of a perfect construction is the careful analysis of the transformer service record as well as the claims and reports sent by the User to the Manufacturer.

The foregoing refers mainly to designers developing specific series and types of transformers covering a number of different ratings. All these problems, however, are beyond the scope of this book.

The transformer design project has a more limited objective, including only construction development of vital parts and assemblies defined by the scope of the course project in accordance with the curriculum. The scope of the design project is refined by the instructor in charge of the project who also determines the procedure of the students' work in realization of the project.

In writing the graduation papers, the extent of the construction development depends on the theme of the project. The work procedure, the scope and the sequence of the design operations are established by the advising instructor assigned to the graduating student.

14.2. Core Construction. Cross Section of Core Legs and Yokes. Steel Stamping. Clamping of Core Laminations. Cold-Rolled Steel Cores. Banding

The main information regarding the basic types and designs of magnetic cores has been presented in Ch. Eleven.

From the design considerations it will be more appropriate, when speaking about the core, to refer to the transformer frame representing the core, clamping bars and other faste-ners. The transformer frame should be mechanically strong and physically stable. These properties are essential because the frame, apart from its main function of providing the path for the main magnetic flux, simultaneously serves as

the transformer foundation. The frame mounts the windings, taps and (in many transformers of sizes I, II, III) the tank cover with terminals, switches and other fittings. ✓

The core construction development is usually started with the calculation of a core cross section to a given diameter.

The diameters are standardized and may be selected from the scale given in Table 14.1.

Table 14.1

Core diameter, D , mm	Number of steps	Number of ducts	Core diameter, D , mm	Number of steps	Number of ducts
80	4	—	340	8	—
90	5	—	360	8	1
100	6	—	380	8	1
110	6	—	400	10	1
125	6	—	420	10	1
140	6	—	450	13	1
160	6	—	480	13	1
180	6	—	500	13	2
200	6	—	530	14	2
220	7	—	560	14	2
240	7	—	600	15	2
260	7	—	630	15	3
280	7	—	670	15	3
300	7	—	710	15	3
320	8	—	750	15	3

For training purposes, any intermediate values of core-circle diameters, multiple of 5, will suffice.

The stepped, nearly round, form of the leg cross section is attributable to the round cylindrical form of the windings seated on the leg. The round form of windings gives the least mean length of the turn (12 per cent shorter than in the case of a square form), which results in a minimum expenditure of copper. Besides, the round coils are more rugged and easier to manufacture.

It is desirable to have the greatest possible number of steps for the circular area to be more completely filled with steel. However, the increase in the number of steps renders the construction and manufacture of cores more difficult

because of the increased number of laminations. Therefore, the number of steps is confined in practice to a certain optimum value depending on the core-circle diameter chosen (refer to Table 14.1).

But the greatest theoretical cross-sectional area of a stepped figure with the same number of steps is obtained only at definite ratios between the width of laminations (or stacks) and the core-circle diameter. These ratios for the

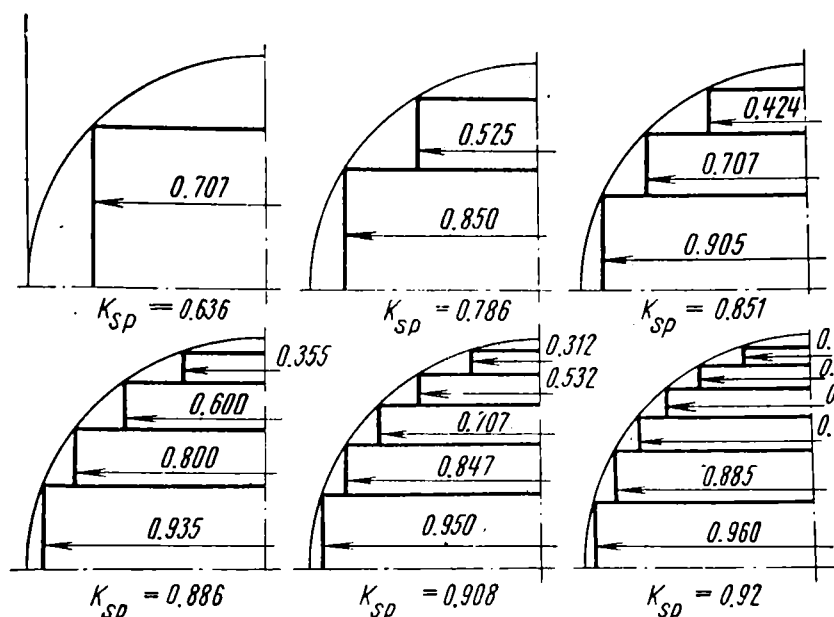


Fig. 14.1. Cross section of stepped legs. (Step sizes for maximum utilization of circle area.)

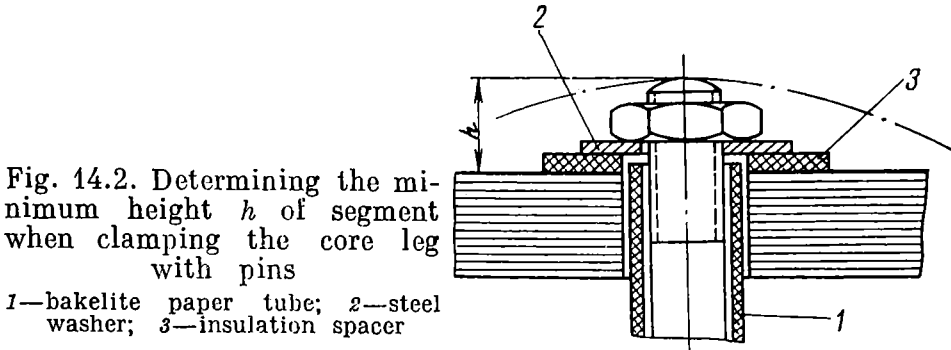
number of steps up to 6 are given in Fig. 14.1. However, in practice one has to depart from the theoretically found sizes of laminations due to the following reasons:

1. The laminations are manufactured in standard sizes (width) to avoid an excessively wide assortment of lamination sizes and to reduce the wastage of steel to a minimum during stamping operations, and the core therefore has to be composed of laminations of standard size only.

When the laminations are stamped from a steel sheet 750 mm wide, their width may be chosen from the following scale: 43, 48, 52, 56, 61, 66, 73, 81, 91, 105, 114, 122, 135, 147, 164, 175, 184, 195, 205, 215, 235, 245, 260, 280, 295, 310, 340, 350, 368, 420 mm. If the laminations are stamped from the steel coils, their width may be the following: 40, 55,

65, 75, 85, 95, 105, 120, 135, 155, 175, 195, 215, 230, 250, 270, 295, 310, 325, 350, 368, 385, 410, 425, 440, 465, 485, 520, 540, 580, 600, 615, 630, 650, 670, 695, 715, 735 mm.

2. When the core-circle diameters are greater than 250 mm, the cores should be clamped together. If the clamping is effected with pins (see below) passed through the



slots punched in the laminations, a space should be provided to accommodate the clamping nuts and washers within the described circle. This space is determined by a segment height h (Fig. 14.2). The minimum height of the segment is chosen against the appropriate core diameter:

Core diameter, D , mm	250-350	350-450	450-500	500-550	550-650	650-750
Segment height h , mm	12	16	22	25	30	35

3. Corrugation and warping of laminations should be taken into account when core diameters exceed 400 mm. For this purpose the mid stacks should be made somewhat thinner so that the stack corners can be slightly short of the circumference. The core section is then inscribed in a circle of a greater radius with its centre accordingly offset.

As has been already stated, the core laminations must be tightly clamped together to ensure:

(a) sufficient mechanical rigidity of the frame and therefore the whole of the transformer structure;

(b) compactness and thereby elimination of corrugation and warping of the laminations and stacks;

(c) stack sizes of the core and yoke according to the drawing;

(d) elimination (or maximal reduction) of vibration and humming of the core when the transformer is running.

The cores of the known power transformer designs are clamped with pins passed through the slots punched in the laminations. The pins must be adequately insulated to prevent their shorting the laminations. Insulation is accomplished by means of bakelite tubes and the insulating washers fitted at the ends of the pins. Steel washers or cover

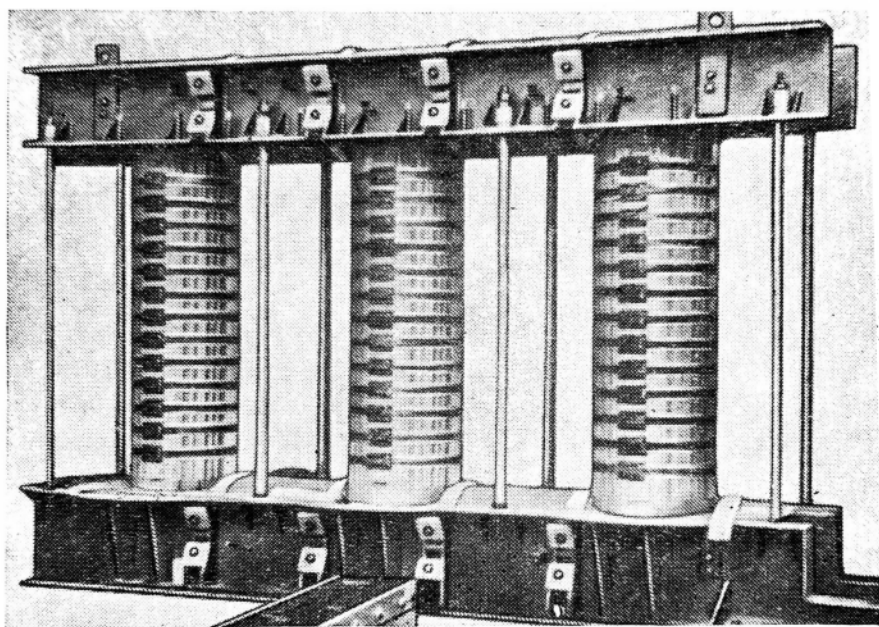


Fig. 14.3. Three-phase core-type transformer with legs clamped by steel bands

plates are then placed over the insulating washers and clamped with nuts. Insulation resistance of the clamping pins is checked by an applied voltage of 1000 to 2000 V.

The cores having a diameter of up to 250 mm are clamped with wooden wedges driven between the winding and the core.

Pins are used for clamping yokes and cores of larger diameter. The pin section is calculated so as to provide a pressure of 3 to 4 kg/cm² per area of the widest lamination after properly tightening the nuts. The clamping nuts and washers placed onto the pins should not protrude over the circumference described around the core cross section (see the reference to Fig. 14.2 above).

This type of clamping cores suffers from serious disadvantages. First, the slots in the laminations decrease the effective section of the core and yoke leading to a local rise of magnetic induction, which in turn increases the no-load

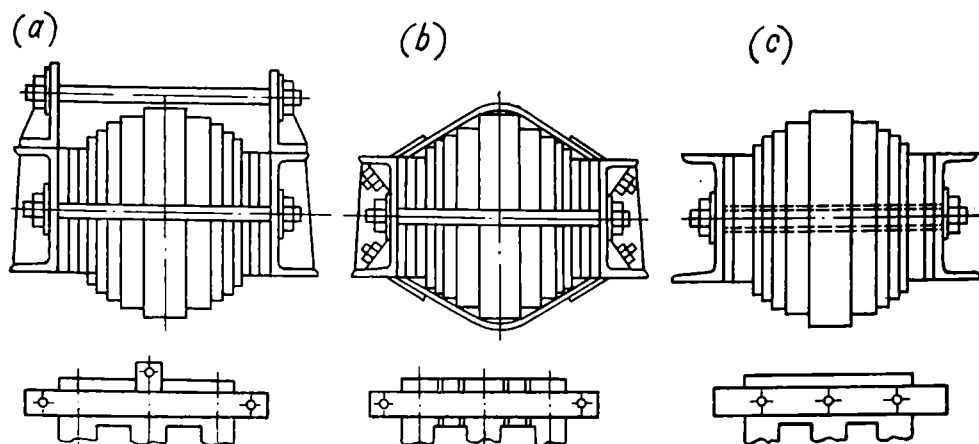


Fig. 14.4. Clamping of yoke with:
(a) external bars; (b) steel straps; (c) clamping studs

current and losses and, second, the punching of slots adds to the cost of manufacture of laminations.

This is why manufacturers are changing over to a so-called pin-free banding practice. The core legs are clamped with bands of metal, glass fibre or glass-tape and the yokes are secured with steel clamps. Fig. 14.3 shows the core secured with steel bands and Fig. 14.4 illustrates various methods of yoke clamping.

14.3. Securing the Windings. Core and Yoke Levelling Insulation

The types of windings and their design have been discussed in Ch. 12. This section describes constructional units associated with fitting, i.e., securing of windings on the core leg. The parts that secure windings serve also as the insulating parts providing necessary insulation gaps.

The LV winding is radially secured on the core leg mainly by means of wooden wedges driven along the core axis and round wooden pins inserted in the corners between the core stacks (Fig. 14.5).

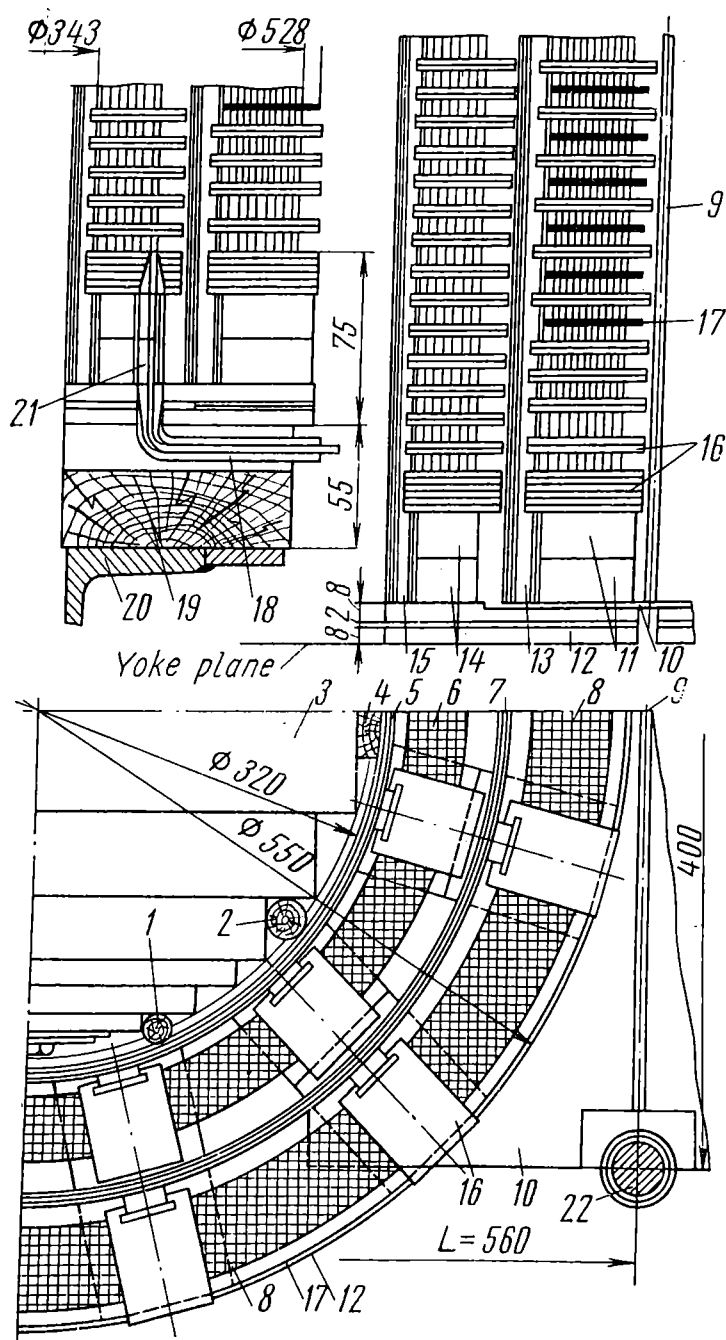


Fig. 14.5. Construction and arrangement of HV and LV windings of three-phase, 1800-kVA, 35/6.3-kV transformer

1 and 2—wooden pegs; 3—core; 4—wooden wedge; 5 and 7—bakelite paper cylinders (LV and HV); 6 and 8—continuous windings (LV and HV); 9—interphase barrier; 10—yoke cover plate; 11 and 14—support rings (LV and HV); 12—yoke insulation; 13 and 15—battens of HV and LV windings; 16—HV winding spacers; 17—pressboard spacer; 18 and 21—LV output end insulation; 19—leveling insulation (wooden plate); 20—yoke bar; 22—vertical steel pin

The multilayer HV windings composed of round conductors are wound around the bakelite cylinders. The HV winding is fastened with battens placed between the LV winding and the HV cylinder.

The continuous HV winding is supported on the yoke insulation. In the case of a two-step or multistep yoke, levelling insulation is mounted on the yoke bars in the form

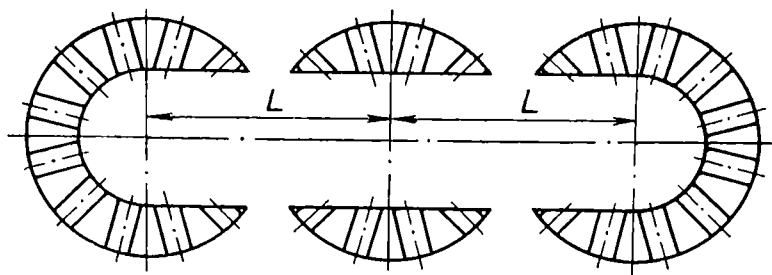


Fig. 14.6. Levelling insulation of three-phase transformer (pressboard strips with back plates)

of wooden planks 19 (see Fig. 14.5) or strips of pressboard with back plates placed underneath (Fig. 14.6).

Figure 14.5 demonstrates a general construction of continuous LV and HV windings and their installation on the core of the 1800-kVA, 35-kV transformer.

14.4. Construction of Power Transformer Tanks.

Tank Shapes and Sizes. Tubular Tanks.

Finned (Radiator) Tanks. Calculation of Tank Mechanical Strength. Design and Construction of Oil Conservators

The oil-cooled transformer tank is an oil container housing the transformer active parts. The oil heated in the progress of transformer operation is cooled through the medium of tank walls and cooling devices.

For the purpose of economy of oil, the tanks are designed to minimum permissible dimensions determined from equations (10.12-10.14) and as shown in Fig. 10.10 above. The tanks are commonly oval in shape. Such a shape more closely follows the form of the active parts of a transformer and is more simple and robust.

The simplest of all, the smooth tanks, are good for transformers up to 40 kVA only. For larger transformers, as has been mentioned above (in 10.6) the cooling surface should be increased either by the use of tubes welded into the tank walls (for power capacity up to 1600 kVA) or by means of radiators (for transformers rated over 1600 kVA).

The external appearance of a tubular tank is shown in Fig. 10.9.

The main parts of an oval tank are the wall, bottom, upper frame and cover manufactured from steel sheets.

The wall usually consists of two parts joined together with vertical welded joints, forming the shell. The lower portion of the shell is butt-welded to the bottom by way of electric-arc welding (Fig. 14.7).

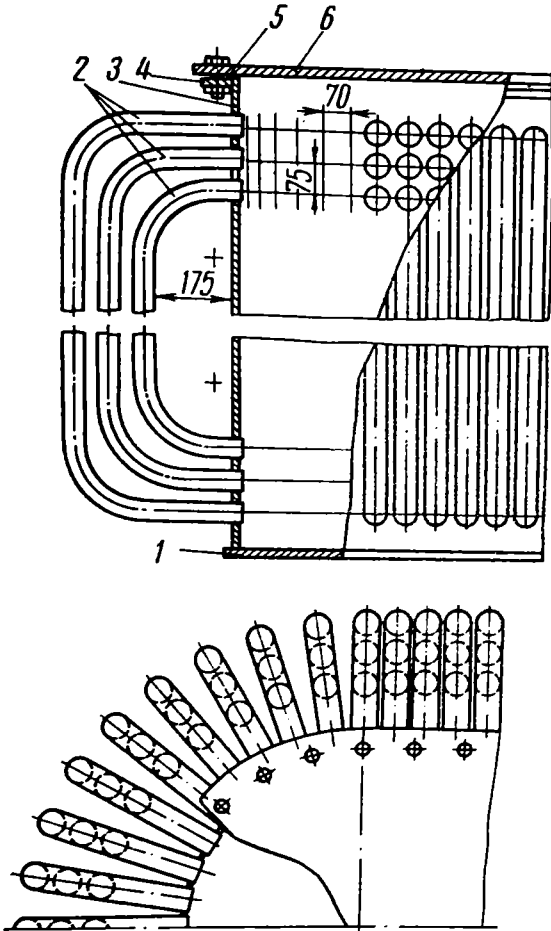


Fig. 14.7. Arrangement of tubes on tank wall

1—bottom; 2—tubes; 3—tank wall; 4—upper frame; 5—cover fastening; 6—cover

Welded atop of the shell is a frame composed of steel strips. The frame has the holes to receive the cover attachment bolts.

The rounded portion of the shell is produced by rolling the steel sheet on the rollers. The shells intended for use with tubular or radiator tanks have the holes for tubes or pipe connections as well as an opening for the drain cock, all of them drilled or punched before rolling and welding.

For the drain cock to be fitted in properly, the tubes over it are made slightly shorter.

Welded to the upper portion of the tank, underneath the frame, are four hooks used for lifting the tank and the whole of the transformer. The tubes situated against the hooks are also made shorter to leave room for ropes.

When designing the radiator tanks, the number and type of cooling radiators (coolers) are determined by thermal calculations. The radiator tank should be constructed so as to obtain the least dimensions in the plan of drawing, see Fig. 10.13.

The coolers are connected to the tank through pipe sockets welded to the tank wall. When fitting in the pipe sockets, it is required to accurately maintain given intervals between their centres along the height and also minimum spacings from the bottom (175 mm) and from the upper frame (170 mm).

The general design of the tank should be consistent with the thermal calculations made. Occasionally, the thermal calculations are made along with a certain amount of construction work which is required to check the spacing of coolers, find the length to which the tubes located against the hooks, plugs and cocks have to be shortened, etc.

As the tank of a transformer is subjected to various mechanical stresses, it must be sufficiently robust. The tank should be designed to withstand a surpluss internal pressure of 0.5 kg/cm^2 . The tank of transformers rated up to 110 kV should withstand a surpluss external pressure of 0.5 kg/cm^2 and that of transformers rated at 220 kV and more, up to 1 kg/cm^2 (when the transformer is vacuum-dried in its own tank).

The tank should also withstand mechanical loads that arise as the result of the transformer lifting in the process of production and assembly at the place of installation. The point is that the transformer is lifted fully assembled and filled with oil (though without coolers). As the transformer is moved by rail, the forces of inertia tend to displace the transformer active parts relative to the tank. These forces should be accounted for when designing the tank.

Calculation of a tank for mechanical strength poses a difficult problem, the more so in the case of large tank sizes. Therefore, a number of assumptions are made to simplify the calculations. Extensive calculations of the tank mecha-

nical properties with regard to its main parts, namely the wall, bottom and cover, are beyond the scope of this book and therefore the calculations involved are given here in a condensed form.

One of the assumptions made in calculation of the mechanical strength of an oval tank is that the strength of the rounded and flat portions is calculated separately, with the flat portion considered as a plate clamped around its contour.

Calculation of resistance to external pressure must be more precise lest the resistance margin of the rounded portion be exceeded.

Taking the margin of stability as 4 and external pressure, 0.5 kg/cm² (for transformers up to 110 kV), the choice of the wall thickness will depend upon the conditions given below.

At $\frac{100\ t}{R} = 0.4, \frac{H_t}{R}$ must be at maximum 0.5

Same	0.5	Same	0.85
Same	0.6	Same	1.4
Same	0.65	Same	1.7
Same	0.7	Same	2.05
Same	0.75	Same	2.4
Same	0.8	Same	2.8
Same	0.85	Same	3.2
Same	0.9	Same	3.6
Same	0.95	Same	4
Same	1	Same	4.5
Same	1.05	Same	5
Same	1.1	Same	5.5
Same	1.15	Same	6
Same	1.2	Same	6.6
Same	1.4 and more	Same	10

Notes. t = tank wall thickness, mm
 R = tank rounding radius, mm
 H_t = tank height, mm

If otherwise, the rounded portion of the wall should be reinforced with horizontal stiffeners or the wall should be made thicker.

The thickness of the flat portion of the wall as a function of its lesser size l (be it length or height) may be selected from Table 14.2.

Table 14.2

Pressure	Maximum length l versus wall thickness, mm				
	3	4	6	8	10
Internal pressure, 0.5 kg/cm ² (all transformers)	500	650	900	1200	1500
External pressure, 0.5 kg/cm ² (up to 110 kV)	420	560	840	1120	1400
External pressure, about 1 kg/cm ² (150 kV and more)	260	350	520	700	870

Problem 14.1. Determine the desired thickness of a tubular tank wall of a transformer rated at 1000 kVA, which dimensions are: $L_t \times B_t = 1440 \times 720$ mm; $H_t = 1500$ mm. The wall thickness $t = 4$ mm will be sufficient for the rounded portion of the tank.

Solution. Verifying by

$$\frac{100t}{R} = \frac{100 \times 4}{\frac{720}{2}} = 1.11; \quad \frac{H_t}{R} = \frac{1500}{360} = 4.17$$

we find that the condition of stability is fulfilled at $100t/R = 1.11$ as the ratio of H/R should be maximum 5.5.

The least size of the flat portion is

$$L_t - 2R = 1440 - 720 = 720 \text{ mm}$$

For a wall 4 mm thick, the maximum size according to Table 14.2 should be 560 mm.

Therefore, the wall thickness should be chosen at 6 mm. Such a tank requires no stiffeners.

The standard specifications prescribe that all oil-immersed transformers of 25 kVA and 6 kV and more should be equipped with expansion tanks (oil conservators). The expansion tank capacity should be so chosen as to keep the tank always filled with oil whatever is the transformer duty (be it off-load or rated load) and at variations of the ambient temperature from -45 to $+40^\circ\text{C}$.

The average temperature rise of oil at rated load is established at 40°C . Thus, the total temperature variation range will be $45 + 40 + 40 = 125^\circ\text{C}$. The coefficient of volume expansion of oil is taken as 0.0007 deg^{-1} . Thus, the maximum possible variation in the volume of oil is $0.0007 \times 125 =$

= 8.7 per cent. Consequently, the total capacity of the conservator should be greater than 8.7 per cent of the oil volume in the tank. It is customary to consider that the conservator capacity should be at least 11 to 12 per cent of the oil volume in the tank (depending on the oil indicator design).

The oil conservator is actually a steel drum horizontally mounted above the tank and connected to it through a tube.

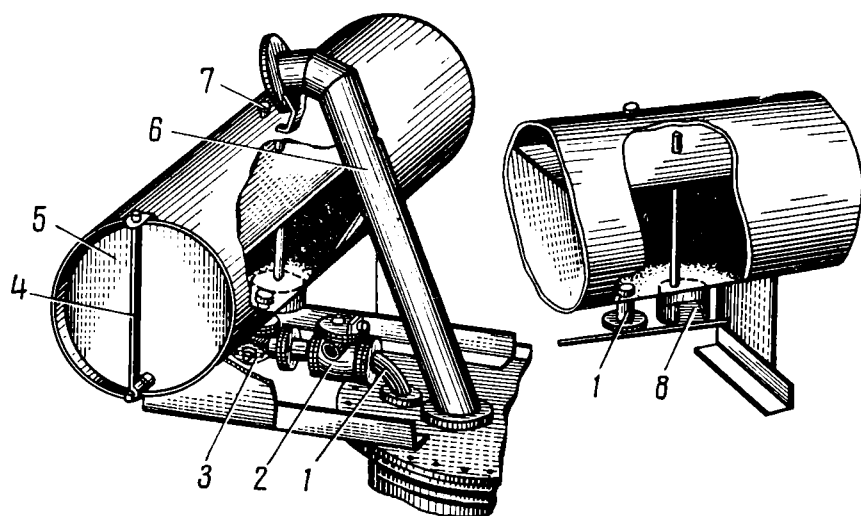


Fig. 14.8. Oil conservator and exhaust tube

1—oil tube; 2—gas relay; 3—shut-off valve for conservator disconnection; 4—oil indicator; 5—oil conservator; 6—relief tube; 7—oil filling plug; 8—oil sump

The conservator should be provided with a detachable bottom or an access hole to enable it to be painted from inside and cleaned from oil sludge.

The conservators are furnished with dehydrators and oil valves. The purpose of these is to remove moisture from the air admitted to the conservator when the oil level drops. The air passes through adsorbing substance (silica gel) and enters the conservator in a dry state. The oil valve removes dust from the air and protects the adsorbing substance against the effect of moisture present in the surrounding medium.

The conservator has an oil-level indicator marked at -45 , $+15$ and $+40^{\circ}\text{C}$ (for the idle transformer). The general view of the oil conservator is shown in Fig. 14.8.

14.5. Auxiliary Protective Devices

Modern power transformers should be equipped with a number of auxiliary devices which help to maintain the normal operation, prevent failures and facilitate servicing. One of these is a gas-actuated relay (Buchholz relay) installed between the tank and oil conservator on the connecting tube. It operates whenever any fault entailing evolution of

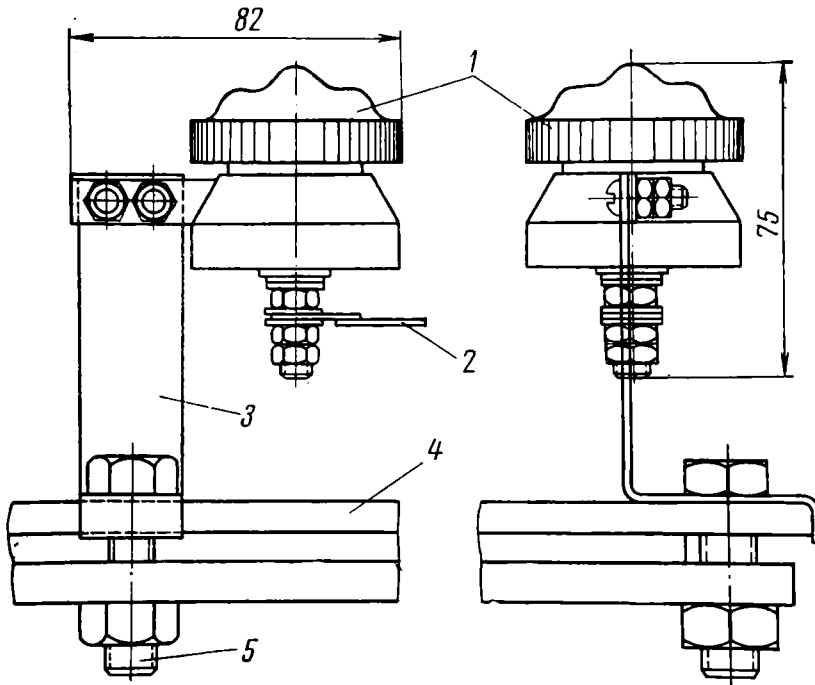


Fig. 14.9. Mounting of circuit breaker for indoor transformer installations (in outdoor installations the circuit breaker is closed with steel cap)

1—circuit breaker; 2—conductor to be connected to LV terminal (230-690 V); 3—steel corner plate; 4—tank cover; 5—bolt

gases, oil leakage and penetration of air occurs in a transformer. The most common relays in use have two contacts, one being an alarm contact, which becomes closed when the gases gradually accumulating inside the relay reach the volume of 250 to 300 cm³, that is, in the case of an incipient trouble. The second contact trips the transformer circuit breaker as soon as the pressure inside the tank rises abruptly, forcing the oil from the tank into the conservator. Transformers of 1000 kVA and more, as well as

indoor transformers of 400 and 630 kVA must be equipped with gas relays.

In case of a serious damage, when the transformer disconnection means somehow failed to operate at proper time, an appreciable pressure may built up in the tank, high enough

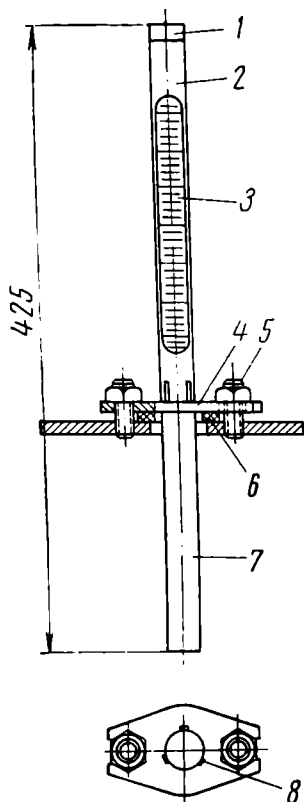


Fig. 14.10. Mounting of mercury thermometer on 25 to 630-kVA transformers

1—case cap; 2—nut; 3—thermometer; 4—steel flange; 5—stud; 6—rubber washer; 7—sleeve; 8—screw

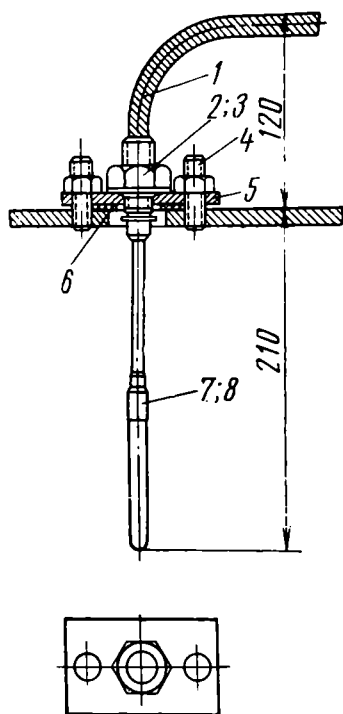


Fig. 14.11. Mounting of temperature detector on 1000—1600-kVA transformers

1—hose; 2—nut; 3—pipe connection; 4—stud; 5—steel flange; 6—rubber washer; 7—tube; 8—temperature sensing bulb

to burst the tank. Furthermore, the leaked oil presents a serious fire hazard. To prevent these occurrences, the transformer cover is provided with a projecting relief tube installed beside the oil conservator. Through this pipe the excess gas and oil are expelled outside. The tube is closed with a glass relief diaphragm which breaks under excessive pressure and thus prevents the tank from bursting. The upper

cavity of the relief tube is connected to the upper part of the conservator through a pipe to prevent the diaphragm from breaking due to an excess pressure brought about by the temperature increase of the oil level in the tube. The relief tubes are installed on the transformers rated at 1000 kVA and more.

The transformers with an HV winding voltage of 690 V and also, on the customer's request, of 230 and 400 V should

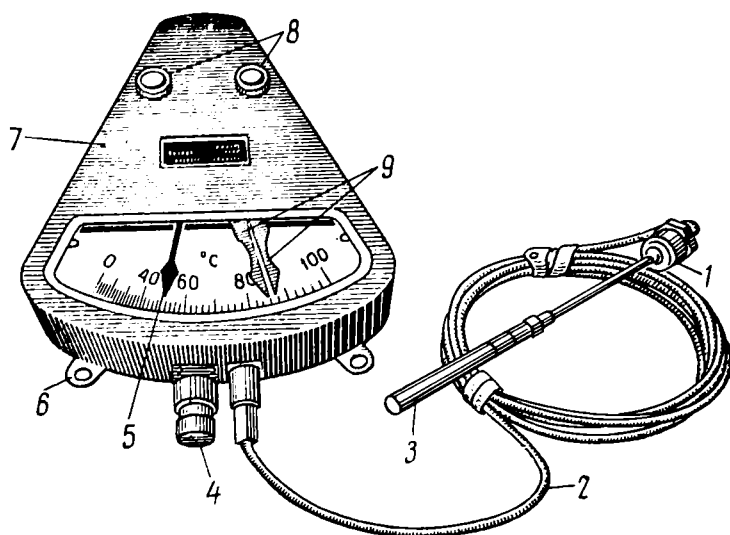


Fig. 14.12. Temperature detector (TC-100)

1—pipe connection; 2—capillary tube; 3—temperature-sensing bulb; 4—binding post; 5—indicator pointer; 6—attachment lug; 7—case; 8—plugs; 9—setting pointer

be equipped with circuit breakers. They prevent the voltage rise on the LV side of the transformer in the event of an electrical breakdown between the HV and LV windings if the mains is not earthed on the LV side. The circuit breaker is a spark gap inserted between the LV winding and earth.

The mounting of the circuit breaker is illustrated in Fig. 14.9.

Temperature of the upper layers of oil in the transformers rated up to 630 kVA is measured by mercury thermometers and in the transformers of 1000 kVA and above, by temperature detectors. A thermometer mounted on the tank cover is shown in Fig. 14.10 and a temperature detector, in Fig. 14.11. The general view of a temperature detector is shown in Fig. 14.12.

Oil deterioration prevention is essential for reliable service of a transformer. Expansion tanks alone do not give complete protection against oil oxidizing. Therefore, trans-

formers of 2500 to 4000 kVA and more make use of oil siphon filters designed for automatic regeneration and cleaning of oil. Such filters are connected to the tank through two pipe unions (similarly to connection of coolers, Fig. 14.13). The filter is composed of a steel

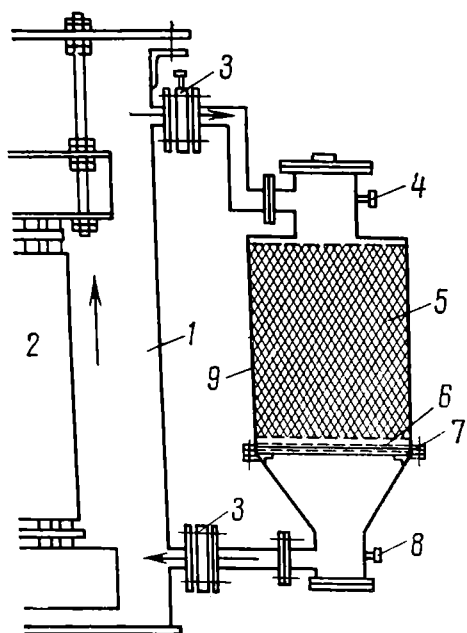


Fig. 14.13. Oil siphon filter

1—tank wall; 2—winding; 3—radiator valve; 4—air bleeder plug; 5—silica gel; 6—gauze; 7—perforated bottom; 8—check plug; 9—filter body

cylinder filled with adsorbent (such as silica gel). The naturally circulating oil passes through the filter from above and silica gel adsorbs ageing products from oil.

14.6. Terminals of Oil-Filled Transformers. Construction of Bushings for 0.5 to 110 kV. Bus Connections

The leads of the oil-immersed transformer windings are brought out through porcelain bushings designed to suit various voltage classes. Besides, the bushings are specifically designed for indoor (up to 35 kV) and outdoor transformer installations.

The bushing consists of a current-carrying part in the form of a conducting rod, bus or cable, and a porcelain cylinder installed in the hole of the cover and used to isolate the current-carrying part.

The porcelain bushing insulator for indoor use has a smooth or slightly finned surface. The outside (upper part) of

the insulator intended for outdoor use is made with petti-coats to protect the lower fins against water in rainy weather. The creepage distance of the porcelain bushings should

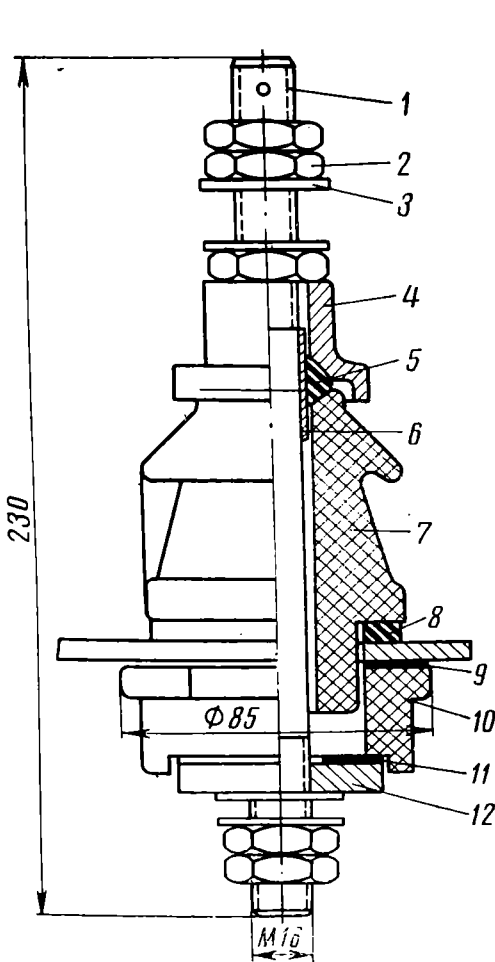


Fig. 14.14. Detachable bushing for outdoor installation, rated at 230-525 V, 400 A

1—copper stud; 2—brass washer; 3 and 12—copper washers; 4—brass cap; 5—rubber ring; 6—copper sleeve; 7 and 10—porcelain insulators; 8—rubber washer; 9 and 11—pressboard spacers

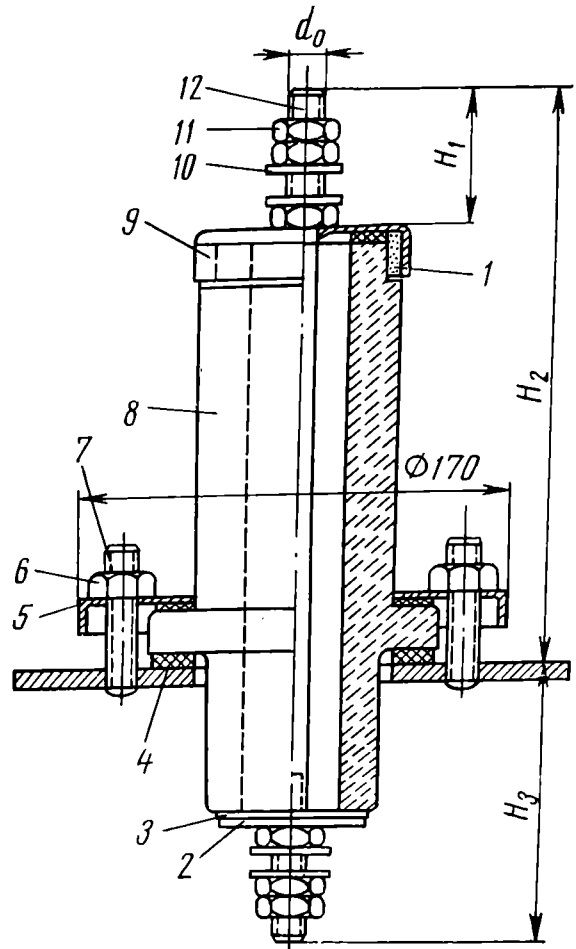


Fig. 14.15. 6-kV bushing for indoor installation

1—magnesia cement; 2—steel washer; 3—pressboard spacer; 4—rubber washer; 5—steel flange; 6—nut; 7—steel stud; 8—porcelain insulator; 9—steel cap; 10—copper washer; 11—brass nut; 12—copper stud

Rated current, A		d_0	H_1	H_2	H_3
275	Type M12	50	225	105	
400	Type M16	55	230	110	

correspond to that given in the appropriate standard specifications. Thus, under normal conditions the creepage distance for the porcelain bushing insulators should be at least

1.75 cm/ $V_{\max}$. This limit is raised to 2.25 cm/ $V_{\max}$ for the regions with fouled atmosphere ($V_{\max}$ is the highest working voltage for the given class).

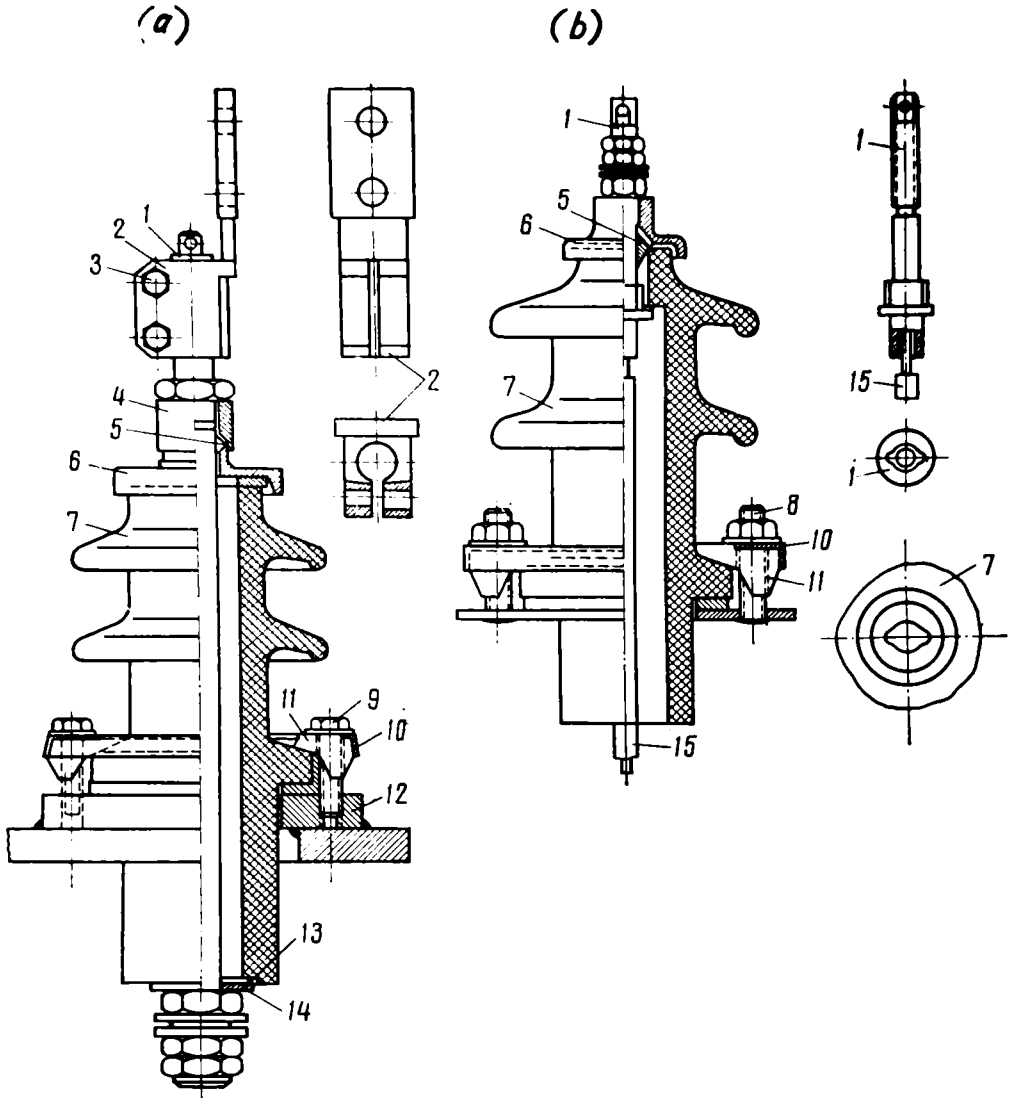


Fig. 14.16. 6- to 10-kV detachable bushings for outdoor installation at rated currents

(a) 800 A; (b) 100 A; 1—copper stud; 2—brass shoe; 3 and 9—steel bolts; 4—brass sleeve; 5—rubber ring; 6—brass cap; 7—porcelain insulator; 8—steel stud; 10—steel flange; 11—aluminium block; 12—slotted plate welded with non-magnetic steel; 13—pressboard spacer; 14—copper washer; 15—paper-insulated conductor

The oil-immersed power transformers have long employed armoured porcelain bushings in which the porcelain insula-

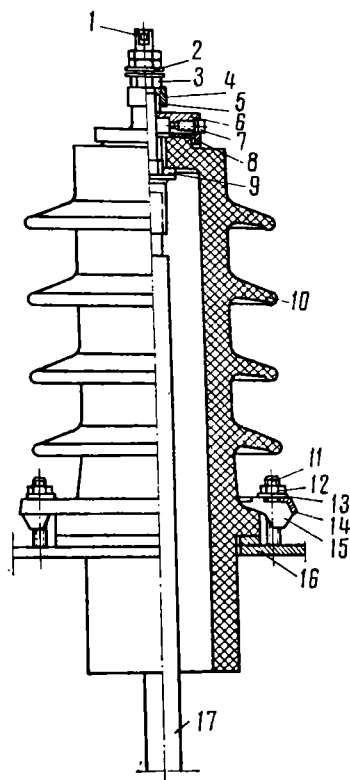


Fig. 14.17. 35-kV detachable bushing

1—stud; 2 and 13—metallic washers;
3 and 12—nuts; 4—sleeve; 5—rubber
ring; 6—metallic cap; 7—air escape
bolt; 8—rubber washer; 9—packing;
10—porcelain insulator; 11—steel
stud; 14—steel flange; 15—block;
16—tank cover; 17—lead

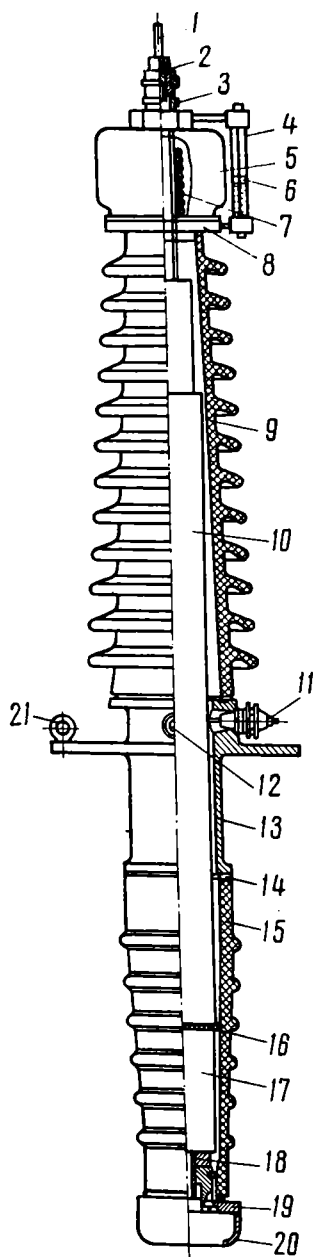


Fig. 14.18. 110-kV, 600-A, oil-filled bushing (type MT-110/600)

1—stud; 2—terminal lug; 3—col-
lar; 4—oil indicator; 5—expansion
chamber; 6—float; 7—spring; 8—
drip pan; 9—upper porcelain cylin-
der; 10—rod; 11—terminal for mea-
suring the tangent of the dielectric
loss angle; 12—means for taking oil
samples; 13—sleeve; 14—sealing wa-
sher; 15—lower porcelain insulator;
16—pertinax washer; 17—insulating
cylinder; 18—copper tube; 19—was-
her; 20—aluminum screen; 21—
lifting eye-bolt

tors were fitted by means of magnesium powder into iron or steel flanges fixed on the tank cover. However, such an insulator is hard to replace and therefore composite and detachable bushings have been recently brought into use. These bushings employed for various voltage classes are shown in Figs. 14.14-14.18.

The transformers designed for supplying electric arc furnaces, where the current reaches a few tens of thousands

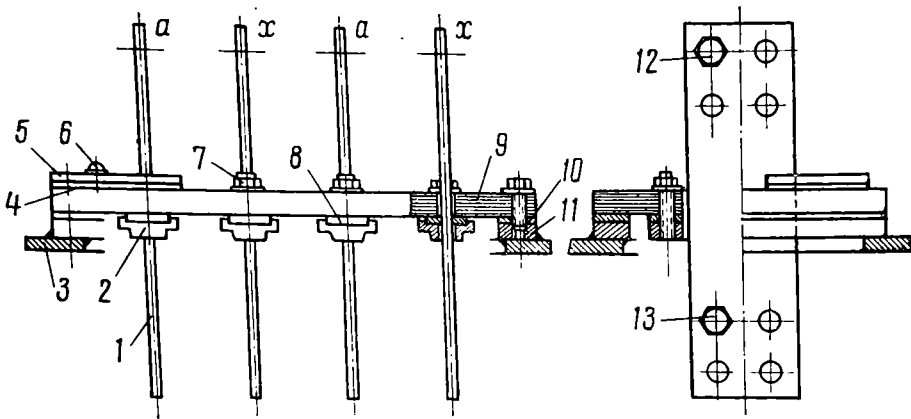


Fig. 14.19. Bus terminal

1—copper bus soldered into holder; 2—brass holder; 3—tank cover; 4, 8 and 10—rubber gaskets; 5—steel plate; 6—steel screw; 7—steel stud; 9—pertinax board; 11—steel flange; 12 and 13—steel bolts

of amperes due to low voltage on the LV side, employ bus terminals. They are composed of copper buses secured on a pertinax board mounted in the rectangular slot of the cover (Fig. 14.19). The bus terminals are more compact, i.e., they occupy less space than the same number of conventional porcelain bushing insulators and, furthermore, they are more easily connected with the bus leads of electric furnace transformers. In view of the fact that the bus terminals are arranged so that their flat parts face each other, the best conditions are obtained for mutual current compensation without a significant rise in reactive voltage drop across the leads.

14.7. Switches and Taps

This section deals with only basic types of switches used for the off-circuit tap-changing arrangements. Description of the on-load switchgear is not presented here as it requires much space. It is extensively covered in Reference [7].

As has been stated in Sec. 9.2 the major off-circuit tap-changing schemes are the centre- and near-the-neutral tapped circuits. The choice of the switch type is governed by the scheme applied. Connections of the centre-tapped circuit are changed by means of a single-phase drum switch, one for each phase. The construction of one such switch rated at 300 A, 35 kV is shown in Fig. 14.20.

The drum switches provide for contact self-adjustment by ring-type contacts (Fig. 14.21). The contact rings turned from a brass tube are seated on a cam shaft and are pressed from the inside to the contact rods by means of helical springs inserted into each ring. The number of rings is chosen to the rated current at which the switch is designed to operate. The cam shaft axle is secured in the middle of two pertinax cover plates. The winding taps are soldered to the ends of the contact rods circularly arranged in the perti-

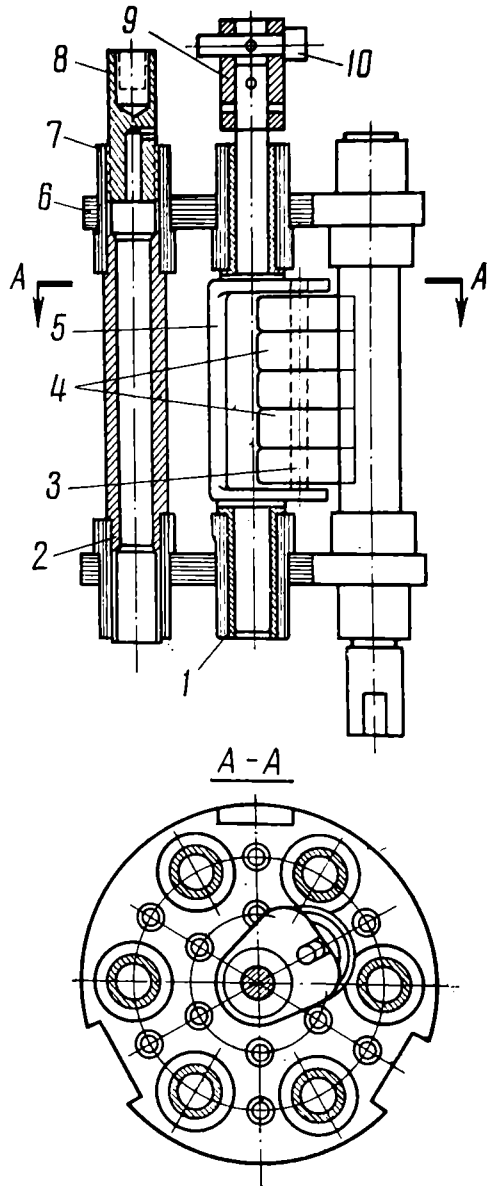


Fig. 14.20. Type II6-300/35 single-phase switch

1 and 9—steel bushings; 2—brass contact tube; 3—ring shaft; 4—brass contact rings; 5—crank shaft; 6—pertinax disc; 7—bakelite paper sleeve; 8—brass tip; 10—steel pin

nax plates. To improve insulation, the rods are inserted into bakelite sleeves fixed in the plates and the cam shaft rotates in two steel bushings pressed into the middle of each plate. The switch is rotated with the help of an insulating rod, the upper end of which terminates in a shaft extended

onto the transformer cover (Fig. 14.22). Each of the five positions of the switch is fixed on the drive cover by locking bolts 7 (Fig. 14.23).

A three-phase switch consists of three single-phase drum-type switches mounted coaxially one atop the other and operated by the common drive. The switches are secured on the active part of the transformer with the use of wooden planks.

The near-neutral tapped circuit (See Fig. 9.2) employs three-phase neutral switches. A construction of a 9-contact, 3-position switch rated at 120 A, 10 kV is illustrated in Fig. 14.24. This switch has self-adjusting segmental contacts 5 which close three adjoining fi-

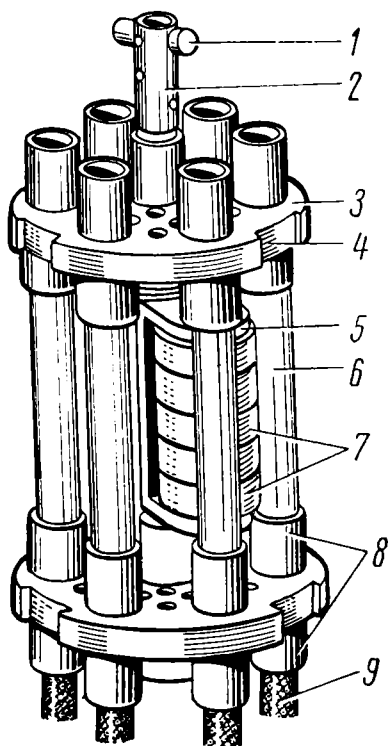


Fig. 14.21. Drum-type switch

1—steel pin; 2—steel bushing; 3—pertinax disc; 4—slot in the disc; 5—crank shaft; 6—contact rod; 7—contact rings; 8—bakelite paper sleeve; 9—cable

xed contacts 2 to which the output terminals of the HV winding are connected. The switch is mounted directly on the cover and is also drive-operated.

The switch is a vital unit of the entire transformer assembly. The most important part of any switch is the set of contacts which must be absolutely reliable in transformer service. The movable parts of the switches need systematic checking, attendance, and supervision. The drive must ensure precise mutual positioning of fixed and moving contacts. The contacts, if offset, may heat and burn which causes the gas relay to actuate and disconnect the transformer. Each particular type of switch is intended for certain current and voltage ratings and the working current through the winding should never be greater than the rated current of the switch.

The conductors forming the transformer electric circuit by connecting correspondingly the output ends and voltage-regulating taps of the winding with the bushings and switches are called the *leads*. These include bare or insulated, round or rectangular copper conductors with associated fasteners; the latter are usually wooden plates fixed on the active parts of the transformer.

The construction of leads depends on the specified HV and LV schemes.

The major problem to be solved in designing the leads is to find their rational arrangement so that with the shortest possible conductors requisite insulation gaps are provided between the conductors, as well as between the conductors and earthed parts according to given voltage ratings. The

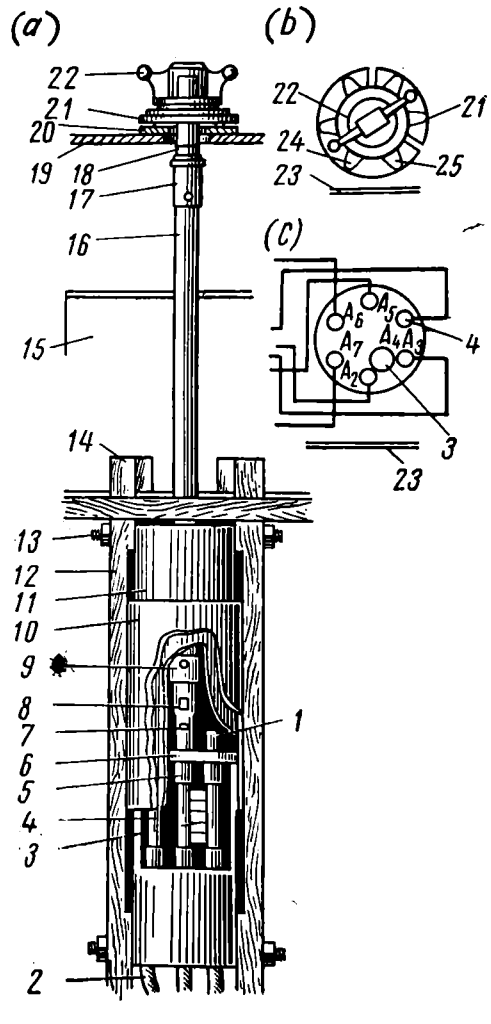


Fig. 14.22. Drum switch assembly
(a) general view; (b) and (c) location of oil gland cover and fixed contacts relative to tank wall; 1 and 11—bakelite paper cylinders; 2—cable; 3—contact rings; 4—contact rod; 5—bakelite paper sleeve; 6—pertainax disc; 7—coupling bush; 8—pin; 9—lower coupling; 10—protective cylinder; 12—wooden support; 13—insulation stud; 14—wooden plate; 15—yoke beam; 16—rod; 17—upper coupling of the rod; 18—drive shaft; 19—tank cover; 20—flange; 21—oil gland cover; 22—drive cap; 23—tank wall; 24—detent; 25—switch position indicator

leads should be so constructed and fastened as to rule out their displacement and excessive bending due to vibration and shocks during transportation of the transformer and also due to possible oil circulation. In the case of large currents, appreciable mechanical stresses might occur in the buses of leads especially under short-circuit conditions.

It is customary to fasten the leads on the top yoke bars to which are welded corner plates with slots for screwing on wooden plates. Fig. 14.25 illustrates a constructional arran-

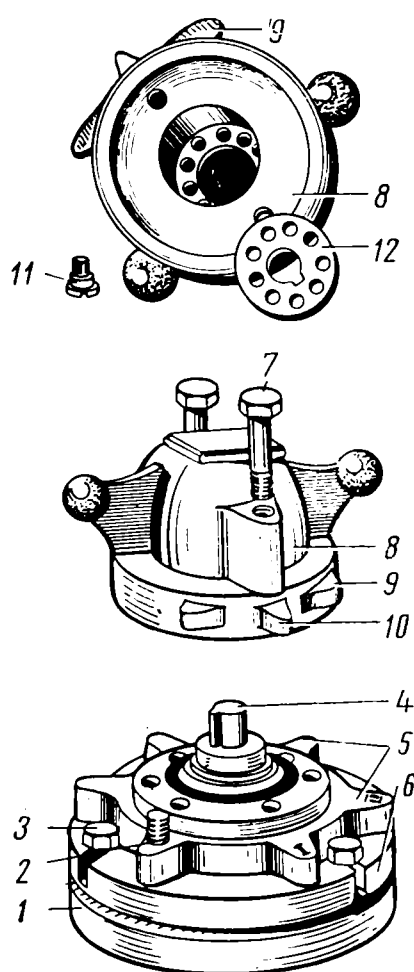


Fig. 14.23. Upper part of drum switch drive

1—flange; 2—stop; 3—bolt; 4—drive shaft; 5—cover lugs; 6—gland cover; 7—locking bolts; 8—cap; 9—stop lug; 10—switch position indicator; 11—screw; 12—vernier ring

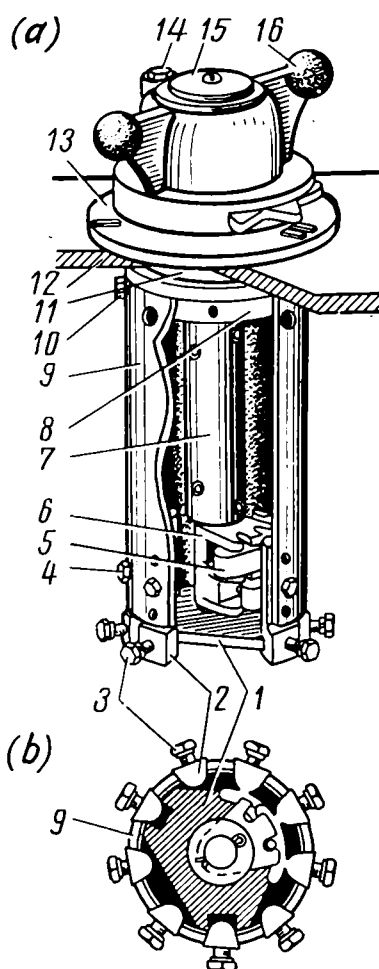


Fig. 14.24. Three-phase neutral switch (type THCV-9-120-10)

(a) general view; (b) bottom view
1—pertinax disc; 2—fixed contact; 3—contact bolt; 4 and 10—bolts; 5—contact segment; 6—crank shaft; 7—insulating shaft; 8—flange; 9—cylinder; 11—rubber ring; 12—tank cover; 13—flange; 14—locking bolt; 15—wooden strip; 16—cap

gement of the HV winding leads of a 3200-kVA, 35-kV transformer.

The lead cross section is determined from the permissible heating under short-circuit and continuous-rated load conditions.

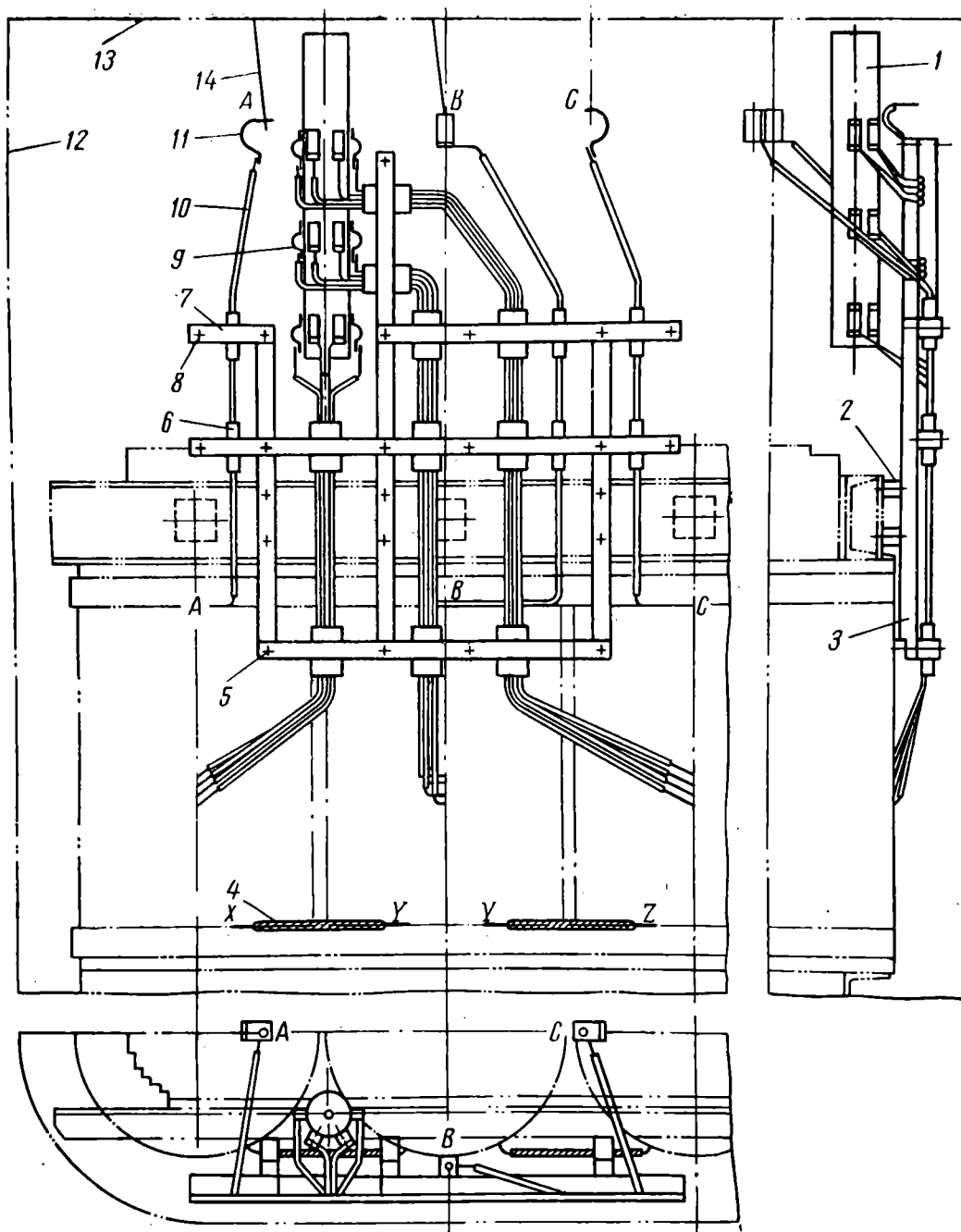


Fig. 14.25. HV leads of 3200-kVA, 35-kV transformer

1—tapping switch (type ICC-4-120/35 × 3); 2—bar; 3—wooden upright; 4—interphase neutral connection; 5—wooden pin with nuts; 6—pressboard; 7—beech holders; 8—steel bolt; 9 and 11—dampers; 10—paper-insulated wire; 12—tank wall line; 13—tank cover line; 14—HV terminal axis

The permissible temperature of the lead during a short-circuit period of 2 to 3s until the actuation of differential protection is maximum 250°C. It is assumed here that the copper temperature rise occurs only on account of the copper specific heat, that is, without heat transfer. Under this assumption the current density in the leads is limited from 4.8 to 5 A/mm².

In continuous operation, the maximum temperature rise of the leads of oil-immersed transformers is not more than 20°C, when the leads are situated above the active parts (in the more heated oil layers) and maximum 25°C when they are arranged at winding height level. The permissible current density δ for round conductors (allowing for a 15 per cent covering of their surface with fasteners) is

$$\text{At } \tau_{lead} = 20^\circ\text{C}, \quad \delta = \frac{16}{\sqrt{d}}, \text{ A/mm}^2$$

$$\text{At } \tau_{lead} = 25^\circ\text{C}, \quad \delta = \frac{18.4}{\sqrt{d}}, \text{ A/mm}^2$$

where d = wire diameter, mm

τ_{lead} = lead temperature rise

Under the same conditions, the permissible current density for rectangular bus leads with a wider bus side placed vertically is the following:

$$\text{At } \tau_{lead} = 20^\circ\text{C}, \quad \delta = \frac{14.55}{\sqrt{1+0.01K_{ex}}} \sqrt{\frac{a+b}{ab}} \text{ A/mm}^2$$

$$\text{At } \tau_{lead} = 25^\circ\text{C}, \quad \delta = \frac{16.75}{\sqrt{1+0.01K_{ex}}} \sqrt{\frac{a+b}{ab}} \text{ A/mm}^2$$

where a and b = bus thickness and width, mm

$K_\Phi = a \left(1.4 - \frac{40}{b} \right)$ is the coefficient of extra losses

Review Questions

1. Why are the sizes of core laminations standardized?
2. What is the purpose of yoke cross section reinforcement?
3. What advantages are gained with the pin-free clamping of transformer cores?
4. How is the form of oil tanks chosen?
5. What kinds of pressure is the tank calculated for?
6. What is the function of an oil conservator? How is its capacity determined?
7. Describe the auxiliary means installed on the transformer tank and their functions.
8. What is the construction and purpose of transformer leads?

Testing and Installation of Transformers and Directions for Use

15.1. Acceptance and Type Tests. Testing the Tanks

All the manufactured power transformers undergo acceptance tests which cover mainly the electrical check-ups.

In production conditions, the acceptance tests represent one of the important steps in checking the quality of manufactured items. These tests are made both at certain stages of production and when the transformer is fully assembled. In the former case transformer basic components are tested, namely, the core, windings, switches, etc., and also some of the magnetic, conductor and insulating materials used in the transformer manufacture.

The acceptance tests are made with a view of revealing defects which may occur in the transformer manufacture and of checking the transformer basic characteristics for conformity to the standard requirements, technical specifications and design data.

The scope of the acceptance tests embraces the following check-ups:

- (a) transformation ratio for all the taps;
- (b) connection group of the windings;
- (c) winding resistance to direct current;
- (d) electric strength of oil taken from the tanks of 35-kV transformers and transformers of more than 1000-kVA, irrespective of voltage;
- (e) the dielectric loss angle of oil in transformers of 110 kV and more;
- (f) insulation resistance of windings relative to earthed parts and insulation resistance between the windings;
- (g) insulation and capacitance dielectric loss angle in 35-kV transformers of 10,000 kVA and more and in transformers of 110 kV and above;

- (h) electric strength of insulation with applied voltage of 50 Hz and with induced voltage of higher frequency;
- (i) open-circuit loss and current (open-circuit test);
- (j) short-circuit loss and impedance voltage (short-circuit test);
- (k) operation of switchgear of on-load and off-load tap changing equipment;
- (l) sealing of transformer tanks (air tightness check).

Each newly developed transformer should be subjected to type tests which, in addition to the above-listed tests, involve the following:

- (m) temperature tests;
- (n) impulse voltage withstand tests;
- (o) short circuit withstand tests;
- (p) tests of the tanks of transformers rated at 1000 kVA and more for mechanical strength under vacuum;
- (q) tests of the tanks for mechanical strength under increased internal pressure.

The type tests are repeated either fully or partially when the design, materials or technology of production are changed so that these changes may influence the transformer performance. The various test procedures are given in the appropriate standard specifications on general tests of transformers, insulation tests, thermal tests, oil tests, etc. The procedure of tests indicated under "p" and "q" above are established by the manufacturer.

Strict observance of a prescribed sequence of test operations is required when testing a transformer since confusion of this sequence might lead to a damage of the otherwise sound transformer. Thus, for example, the electric strength of the transformer insulation must be tested only after testing the transformer oil in the tank and measuring the insulation resistance. If this sequence is not observed, a breakdown of the electrical insulation may occur due to, say, improper drying of the transformer — a defect which can be easily disclosed if the insulation resistance tests and oil sampling are done first.

When testing the electric strength of insulation with applied voltage, insulation of individual turns may be damaged by partial discharges, which may lead to an interturn short circuit and puncture of the conductor insulation. For

such a damage to be disclosed, the induced potential tests must be conducted after the applied potential tests.

It is good practice to make an open-circuit test after an induced-potential test in order to detect a puncture of the conductor insulation which may have occurred either in the last seconds of the test or as voltage is removed.

The resistance of windings to direct current should be measured after completion of the open-circuit test if the state of the soldered joints and contacts is to be checked upon energizing them with direct current.

Thus, the following test sequence is advised:

- (1) electric strength of transformer oil;
- (2) winding insulation resistance;
- (3) electric strength of insulation with applied voltage;
- (4) electric strength of insulation with induced voltage;
- (5) open-circuit conditions.

Following these tests, the short-circuit test and measurements of the direct-current resistance of the windings may be made. The sequence of measuring the transformation ratio and determining the winding phasor group is optional.

The acceptance tests are subdivided into proof and final tests.

The proof tests are applied to individual parts and units of a transformer in the process of manufacture and assembly. The purpose of proof tests is to prevent faulty parts and units from being installed in the transformer and check those parts and units which cannot be tested in the finished transformer. These are primarily the windings, cores, and switches.

The scope of the proof tests is defined by the manufacturer depending on the state and quality of production.

All the windings, being the vital parts of any transformer, undergo the proof tests. The responsibility of the winding workshop quality inspectors is to check the number of turns and to examine them for interturn shorts.

The magnetic cores (frames) of transformers are tested for the quality of insulation of the clamping pins, if any, and strength of the varnish insulation of the laminations. The insulation of the clamping pins, yoke bars, cover plates, and other parts from the ferromagnetic steel of the core is tested with an applied voltage of 1000 to 2000 V of indu-

strial frequency for one minute. The quality of the lamination insulation is checked by measuring the resistance to direct current between the extreme laminations and between separate stacks of the core.

The tests of the switchgear are subdivided into electrical and mechanical. First to be made are the mechanical tests of contacts for mechanical strength and contact pressure (measuring by a dynamometer). The tested switch should

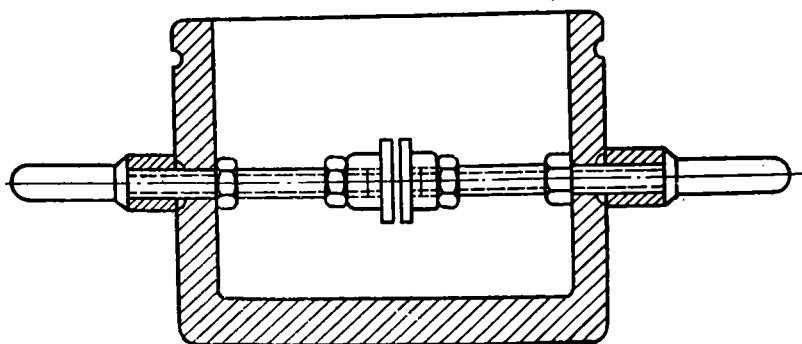


Fig. 15.1. Standard discharge tube (evacuated enclosure with electrodes) for testing the electric strength of oil

be closed and opened a specified number of times and then checked for damage of contacts, springs and coating.

The electrical tests involve checking the electric strength of insulation:

- (a) between the switch contacts of each phase branch;
- (b) between the phases;
- (c) between all the contacts and the switch axle;
- (d) of the insulated portion of the switch shaft.

The final tests are made on the fully-assembled and dried transformers enclosed in tanks and filled with oil.

For checking the electric strength of oil, an oil sample is taken from each transformer with the voltage class of 35 kV and above. In the case of transformers of sizes I and II, rated below 35 kV, the oil samples can be taken either from one transformer of the batch or from the oil container used for filling the transformers.

The electric strength of oil is tested in a standard discharge tube (Fig. 15.1) with the electrodes spaced 2.5 mm apart. The electric strength of the oil sample should be not below 40 kV. The breakdown voltage is determined as the arithmetic

tic mean of the five out of the six breakdowns (the first disruptive discharge is disregarded).

A great insulation resistance level of the tested transformer winding is an evidence of the fact that the transformer is free from grave defects, that it is clean and well dried. This also warrants its immunity to damage that may occur during electric strength tests. Besides, correlation of the insulation resistance values obtained before commissioning the transformer with those obtained before putting it into

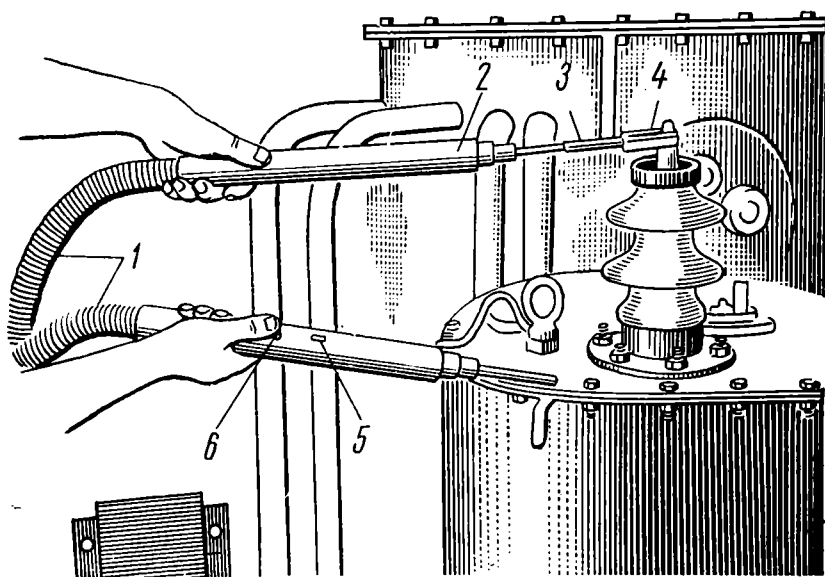


Fig. 15.2. Measuring the insulation resistance

1—portable connecting wires; 2—bakelite tube; 3—copper rod; 4—clip; 5—pilot lamp; 6—signal button

service in combination with other indices makes it possible to assess the degree of dryness of the transformer and the likelihood of its use without additional drying. No limitations are imposed on the absolute resistance inasmuch as this value is impossible to ascertain due to various reasons. The insulation resistance of the windings depends on their dryness and temperature and is measured by means of a megger between each winding and earth and between the windings of different voltages as shown in Fig. 15.2.

The megger readings are not constant because a certain amount of time is needed till the magnetic field in the winding is stabilized. Therefore, to assess the degree of dryness of the winding insulation, two readings are taken, one after

15 seconds and the other after 60 seconds. In the event of highly humid insulation, the megger promptly comes to equilibrium and the absorption factor is nearly unity, $K_{ab} = R_{60}/R_{15}$. If the insulation is but slightly moistened,

the megger pointer climbs slowly and the absorption factor may equal two and more (but not below 1.3).

The insulation resistance of the windings depends to a great extent on temperature, so the comparative measurements are made at the same temperature. If the subsequent measurement is taken at a different temperature, the value of both the measurements are corrected to one and the same temperature. In this case the assumption is that insulation resistance rises ab-

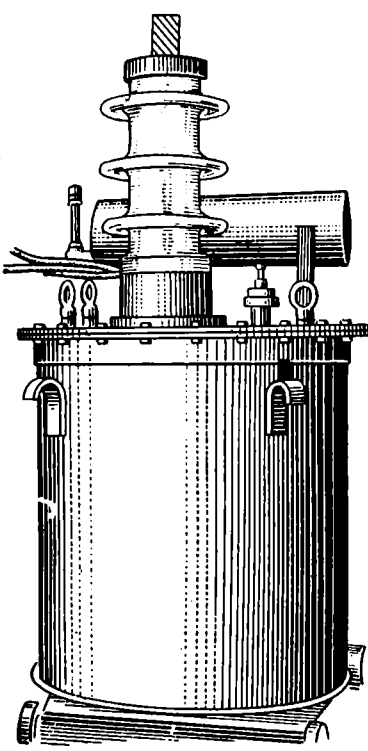


Fig. 15.3. Type NOM-100/100, 100 kVA, 100/0.38 kV test transformer used for applied potential tests of 10 to 35-kV transformer windings

out 1.5 times during one minute with each 10-degree drop in temperature. Hence, the following corrections should be introduced:

Temperature difference	5	10	15	20	25	30	35
Insulation resistance increments	1.2	1.5	1.8	2.3	2.8	3.4	4.1

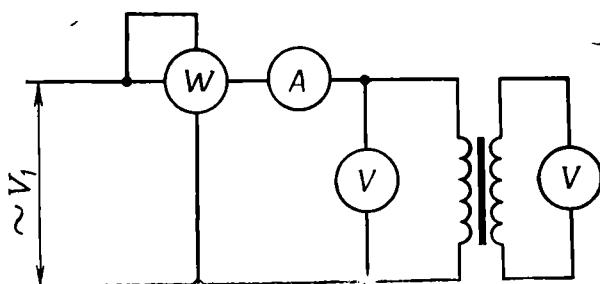
The tests of the electric strength of insulation of the windings and current-carrying parts with applied and induced test voltages were discussed in considerable detail in Sec. 13.3 above.

The general view of the test transformer, whose diagram is shown in Fig. 13.1, is illustrated in Fig. 15.3.

The open-circuit test (Fig. 15.4) is used to determine no-load current and open-circuit losses and to check the transformation ratio. The secondary of the transformer is open-circuited and an alternating voltage is applied to the pri-

mary. The measuring instruments connected into the circuit, ammeter A and wattmeter W , indicate the no-load current and losses of the transformer. The parameters measured by the instruments should not be greater than the

Fig. 15.4. Open-circuit test diagram for single-phase transformer



values specified by the appropriate standard specifications (tolerances considered). The transformation ratio is determined from the indications of the voltmeter (on all the

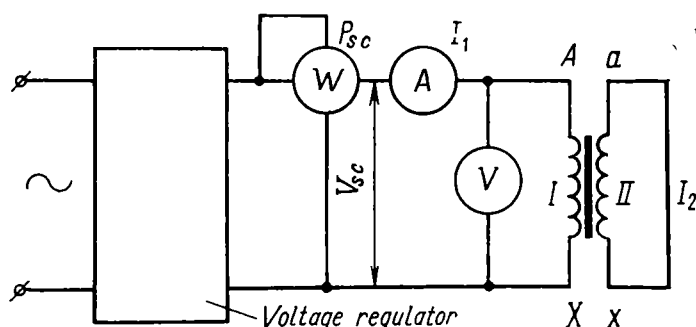


Fig. 15.5. Short-circuit test diagram for single-phase transformer

voltage regulating steps), which should not differ from the specified value by more than $\pm 0.5\%$.

The purpose of the short-circuit test (Fig. 15.5) is to determine the short-circuit losses and impedance voltage. In this case the secondary winding of the transformer is short-circuited (say, to an ammeter) and the primary winding is excited with a low voltage which is raised from zero until ammeter A reads a rated current. This voltage is applied through a suitable voltage regulator. Voltage V_{sc} given by voltmeter V is called the *impedance voltage* representing the full impedance voltage drop across the transformer. The impedance voltage is demonstrated on the phasor diagram of the impedance voltage triangle (see Fig. 5.4)

by the hypotenuse. During short-circuit tests rated currents are established in both windings because their magnetomotive forces (according to Lenz's law, Sec. 5.1) must be equal. Therefore, wattmeter W will indicate the total losses in both windings, called the *short-circuit losses*. The open circuit losses are small and therefore neglected (EMF during short-circuit tests is about $1/2 V_{sc}$, and magnetic flux is thereby low).

The resistance of the transformer windings to direct current is not limited in the technical specifications. Nevertheless, the measurement of the winding resistance is a compulsory routine during acceptance tests because it helps to disclose the defects in the current-carrying parts of a transformer. The results of these measurements furnish the helpful data regarding the quality of the connections and soldered joints in the windings, the quality of contacts in the switches and at the junctions of taps and leads, the absence of breaks in the windings or in their individual parallel branches. This data enables us to detect whether the cross section of conductors between the individual phases or between the coils of one phase differs from the rated value. Measurements of the winding resistance are also suitable for determining the average temperature of the windings (temperature measuring technique is discussed in 10.2).

The winding resistance is measured in all the windings across each accessible branch. In the case of three-phase transformers, the resistance of each winding is measured for all the three phases. If a neutral connection is available the phase resistance is measured, if not, the line resistance. In the latter case the phase resistance $R_{ph} = 1/2 R_{mea}$ with a star connection and $R_{ph} = 3/2 R_{mea}$ with a delta connection.

If different results have been obtained on measuring the line resistance of windings (connected in star), the phase resistance can be found from the following equations:

$$R_a = \frac{R_{ab} + R_{ac} - R_{bc}}{2}$$

$$R_b = \frac{R_{ab} + R_{bc} - R_{ac}}{2}$$

$$R_c = \frac{R_{ac} + R_{bc} - R_{ab}}{2}$$

Should the discrepancy in resistances of different phases exceed ± 2 per cent of the mean value, the cause of this discrepancy should be found in order to determine whether the transformer is fit for further use.

The winding resistance is commonly measured by a voltage drop method based on Ohm's law.

Test circuits are shown in Fig. 15.6, which are selected depending on the resistance

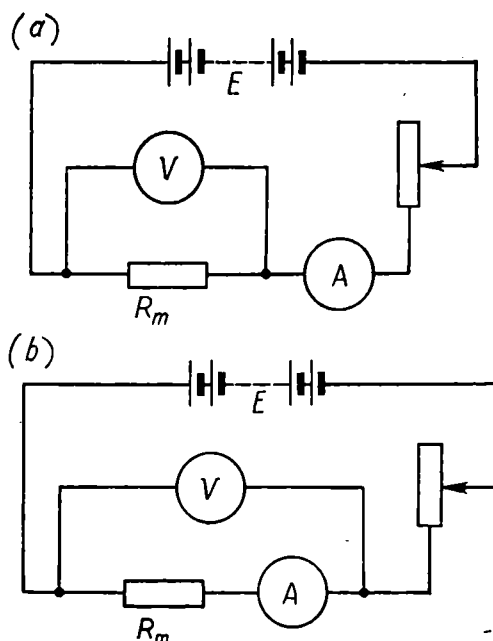


Fig. 15.6. Diagrams for measuring transformer winding resistance

(a) at small resistance; (b) at large resistance

value. The test set incorporating an electric circuitry and a power supply (a 12-V storage battery) is shown in Fig. 15.7.

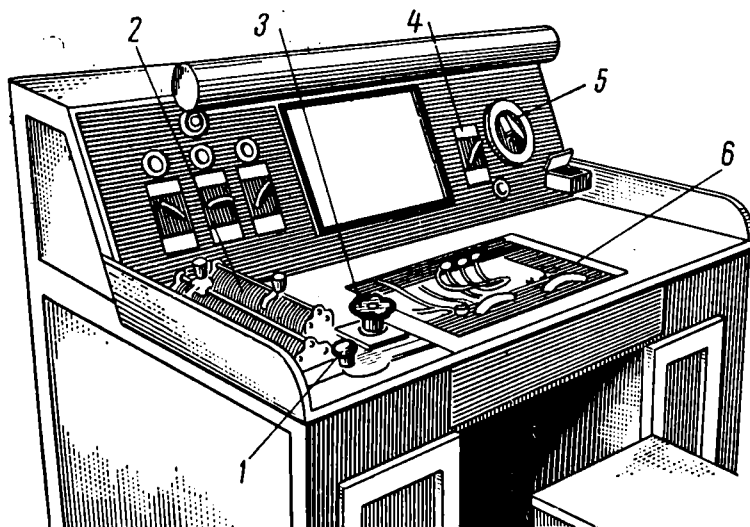


Fig. 15.7. Panel for measuring resistance by voltage drop method
1—cabinet with instruments; 2—rheostats; 3—phase switches; 4—connection switch; 5—ammeter shunt; 6—contactor button

The phasor group of the transformer windings is instrumental when transformers are connected for parallel opera-

tion. This operation is permissible only for transformers with an identical phasor group.

The standard phasor groups are 0 for single-phase transformers and 0 and 11 for three-phase transformers.

Phasor groups are checked mainly by two methods, the first involves the use of two voltmeters and the second is accomplished with a phase meter.

In the former case a decreased voltage is impressed across one winding of a three-phase transformer after interconne-

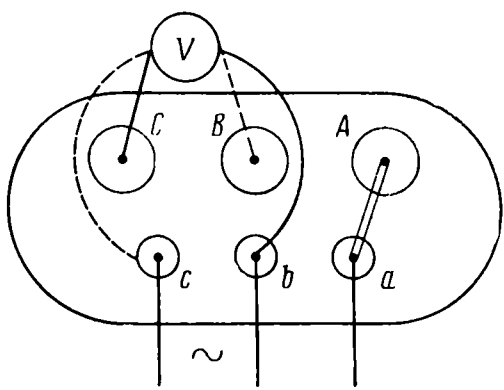


Fig. 15.8. Determination of connection group of three-phase transformer

cting like leads *A* and *a* of the HV and LV windings. Then, the voltages between leads *b-B*, *b-C*, and *c-B* are alternately measured in the manner shown in Fig. 15.8. The phasor group is found from a special table by using the results of three measurements.

Thus, the measured voltages for standard phasor groups 0 and 11 should be equal to those indicated in Table 15.1 that follows

Table 15.1

Phasor group	Angular displacement of EMFs degree	Voltage across leads		
		<i>b-B</i>	<i>b-C</i>	<i>c-B</i>
0	0	$V(K-1)$	$V\sqrt{1-K+K^2}$	$V\sqrt{1-K+K^2}$
11	330	$V\sqrt{1-\sqrt{3}K+K^2}$	$V\sqrt{1+K^2}$	$V\sqrt{1-\sqrt{3}K+K^2}$

(*K* is the transformation ratio).

The acceptance tests include also the testing of oil tanks for mechanical strength and oil leakage of welded and sealed joints.

When in service, the tank is filled with transformer oil. Since the oil level is above the tank cover (at oil conservator level), the tank should be tested for an increased internal pressure. For this, a tube 1.5 m high is fixed on the tank cover and is filled with oil. The transformer is then carefully wiped dry and allowed to stand for eight hours. The tank is regarded as good if no traces of oil leakage through the welded and sealed joints are detected.

When vacuum drying the active parts in the transformer tank, the latter is held at an external pressure of about 1 kg/cm^2 . Therefore, this pressure is taken as the reference one when calculating the mechanical strength of the tank.

15.2. Transportation, Storage and Installation

Power transformers of sizes I, II and III are carried from the manufacturer to the user mostly by rail. Transformers provided with tubular tanks (up to 1600 kVA) are transported fully assembled and filled with oil. Transformers with radiator tanks (2500 kVA and more) are transported with the conservator, radiators, and relief tube removed. Pipe sockets connecting radiators are closed with caps when in transit.

The railroad regulations influence to a certain extent the construction of power transformers. Mainly, this refers to large-size transformers which have to comply with railroad clearances and load capacities of the rolling stock.

Thus, transportation of transformers of sizes III, IV and larger necessitates their partial dismantling, calls for use of tanks of particular shape, transport covers, and special railway wagons with lowered cargo platforms. To decrease the shipped weight, the large transformers have to be dispatched without oil and the tanks have to be temporarily filled with inert gas (nitrogen). All this entails extra work at the place of installation.

To ensure safety, the transformer should be reliably secured on the wagon.

Each power transformer is furnished with accompanying technical papers containing a technical description and instructions for transportation, unloading, installation and commissioning of transformers. It is the customer's duty to abide by the instructions and recommendations contained therein.

Before reassembly of the shipped transformer, the attending personnel should read the accompanying papers, make ready the assembly site, the requisite equipment and materials, as well as prepare the transformer and its component parts for reassembly.

The assembly site should be equipped with a temporary shelter and lifting equipment, such as a railway crane or a lorry crane, jacks, etc.

The oil-immersed transformers should be lifted only by the hooks provided under the frame on the tank wall.

Once delivered to the point of destination, the transformers should be examined for the condition of porcelain bushings tanks, cooling devices, seals, etc. The inspecting personnel should also check the level of oil and make certain there is no oil leakage.

It is not always the case that the shipped transformer is reassembled immediately upon arrival. Therefore, provisions should be made for its proper storage.

The indoor transformers should be stored in a weather-proof enclosure.

The transformers should be well guarded against mechanical damage and ingress of dirt. When in storage, the oil level in the conservators should be maintained at normal level and dry (water-free) oil with electric strength not below 45 kV per 2.5 mm should be added whenever required. Preservation lubricant and silica gel should be reconditioned at least every two years and whenever thought necessary.

After installation of the transformer on the assembly site and reassembly, it should be prepared for use after performing a number of preventive maintenance operations.

First of all, the transformer should be examined visually. Special attention must be paid to the welded and sealed joints (to be checked for oil leakage). Then, the level of oil is checked and oil is added, if needed. The thermometer case is filled with oil, the porcelain bushings are wiped clean by

petrol and dry cloth and the preservation lubricant is removed. The transformer is then earthed by the earthing bolt.

Next, the sample of oil is tested for electric strength and chemical content. The electric strength should be not below 40 kV per 2.5 mm. The chemical analysis should prove that oil is free from traces of water. The oil samples are taken at a temperature not lower than $+5^{\circ}\text{C}$. Other tests involve application of a 1000-V megger for measuring the insulation resistance of the HV and LV windings. The insulation resistance should be not less than 300 megohms at a temperature corrected to $+20^{\circ}\text{C}$. These measurements should be made at a temperature not below $+10^{\circ}\text{C}$. The resistance of the windings should be measured in all switch positions. Finally, the condition of silica gel in the dehydrator is checked and replaced if deteriorated.

If the above-stated tests and checks yield positive results, the transformer may be placed on a footing and connected to a power supply. Then the switch is flipped directly to the full rated voltage. As soon as the full rated voltage is applied, the attending personnel should ensure that the phases are loaded uniformly, voltage on the LV side is symmetrical, oil level in the conservator is maintained normal, and temperature rise of the upper layers of oil is not higher than 55°C .

15.3. Basic Safety Regulations

Permanently connected lightning arresters and relay-operated and gas-actuated disconnecting facilities designed to protect the transformer and its line terminals are indispensable for transformer service.

The waveform of the voltage applied to the transformer should be practically sinusoidal and the system of the phase voltages virtually symmetrical.

The transformer is not allowed to operate whenever the oil level descends below the lower notch of the oil indicator and should be barred from further use in the presence of oil leakage.

The attending personnel should visually check the condition of contacts of the operating transformer. It is also the duty of the attending personnel to keep dirt and dust away

from the tank cover, buses and leads. All damages to anti-corrosive coating should be corrected as soon as detected.

It should be remembered that the voltage steps should NEVER be changed if the transformer with the off-circuit tap changer is connected into the mains even on one side only.

The running transformer may produce a low droning noise which is not objectionable as long as it is free from cracking and rattling.

15.4. Load Capacity

The transformer is designed for continuous operation at rated load and allows a continual 5-per cent rise over the rated current, provided that the voltage does not go beyond the rating.

Table 15.2

Overload factor, K_0 (%)	Permissible overload time (hours, minutes) versus overheating (in degrees C) of upper oil layers before overloading					
	18	24	30	36	42	48
5	5-50	5-25	4-50	4-00	3-00	1-30
10	3-50	3-25	2-50	2-10	1-25	0-10
15	2-50	2-25	1-50	1-20	0-35	—
20	2-05	1-40	1-15	0-45	—	—
25	1-35	1-15	0-50	0-25	—	—
30	1-10	0-50	0-30	—	—	—
35	0-55	0-35	0-15	—	—	—
40	0-40	0-25	—	—	—	—
45	0-25	0-10	—	—	—	—
50	0-15	—	—	—	—	—

Table 15.2 contains permissible short-time overloads given as functions of the initial temperature rise of the upper layers of oil over the ambient air temperature.

The above-given table is drawn for an outdoor-type transformer at an average annual temperature of $+5^{\circ}\text{C}$ (most common for the central regions of the USSR). For regions with other average annual temperatures the value of overloading $1 + \frac{K_0}{100}$ found from the table, should be multi-

plied by $1 + \frac{5 - T_{av}}{100}$, where T_{av} is the average annual temperature for a given area.

Problem 15.1. With oil overheating of 30°C, a 30 per cent overload is permissible for 30 minutes. Determine the overload factor for the area with an average annual temperature +15°C.

Solution. The permissible overload is $1.3 \left(1 + \frac{5 - 15}{100} \right) = 1.17$ of the rated value, i.e. the overload factor is 17%.

15.5. Fault-Finding Chart

Table 15.3

No.	Symptom	Possible cause	Remedy
1	Transformer automatically disconnected by overcurrent protection	1. Overcurrent impermissibly high 2. External short circuit	1. Decrease current to rated value 2. Eliminate short circuit
2	Transformer automatically disconnected by differential and gas-relay protection	Incipient trouble	1. De-energize transformer 2. Determine gas content 3. Take oil sample for brief analysis, including flash temperature measurements 4. Measure insulation resistance and check the winding continuity 5. Inspect transformer active parts
3	Transformer automatically disconnected by gas-operated relay	1. Residual air escape after assembly 2. Incipient trouble	1. Determine gas content 2. Make a trial connection under open-circuit and short-circuit test conditions, gradually stepping up voltage in order to locate point of fault, whether it is winding with contact joints or magnetic core (refer also to item 2 above)

Continued

No.	Symptom	Possible cause	Remedy
4	Loss of voltage on secondary side	Break in one of the windings	1. Apply megger or measure winding resistance and locate a point of interruption 2. Inspect transformer active parts
5	High-pitch uneven noise inside transformer	1. Upset conditions of power supply and load 2. Incipient trouble 3. Loose parts	1. Restore normal operating conditions 2. Check against No. 2 above (omitting determination of gas content) 3. Secure loose parts
6	Oil leakage through sealed joints	Sealed joint leaky	Tighten up bolts in sealed joints or replace sealing gasket
7	Damage to porcelain bushing	Mechanical damage	1. Shut off cock between conservator and tank 2. Drain necessary amount of oil from tank 3. Replace porcelain or entire bushing
8	Glass tube of oil indicator damaged	Mechanical damage	1. Close oil indicator 2. Replace glass tube

Review Questions

1. Name the basic kinds of acceptance tests of power transformers.
2. Which of the transformers undergo type tests?
3. Why is it necessary to observe the sequence of test performance in certain kinds of tests?
4. What is the purpose of the no-load test? Illustrate the test diagrammatically.
5. What is the purpose of the short-circuit test? Illustrate the test diagrammatically.
6. Why do large-size transformers need partial dismantling when transported?

Transformer Economy

16.1. Elements of Transformer Cost

The transformer cost (wholesale price) is determined on the basis of the planned calculation.
An example of drawing planned cost accounts is given below in Table 16.1.

Table 16.1

Transformer, type
Outline drawing Gross weight kg

No.	Item of expenditure	Cost in rubles
1	Materials and raw products	
2	Standard and purchased items	
3	Reusable refuse (to be subtracted)	
4	Total basic materials	
5	Payment of production workers	
6	Maintenance (150 to 200% of wages and salaries)	
7	Workshop expenses (about 150% of wages and salaries)	
8	General transformer-building plant expenses (about 100% of wages and salaries)	
9	Plant cost price	
10	Administration costs (about 5% of plant cost price)	
11	Full cost price	
12	Interest (10% of full price)	
13	Wholesale price	

Consumption of basic materials is given in Tables 16.2 and 16.3

Table 16.2

No.	Name of materials and raw products	Unit of mea- sure	Con- sump- tion	Cost- rubles, copecks	Total expenses, thousands of rubles
1	Iron casting				
	Steel casting				
	Casting total				
2	Rolled stock:				
	Sheet steel				
	Coiled steel				
	Profile steel				
	Rolled stock total				
3	Special rolled stock:				
	Electrical steel				
	Hot-rolled profile steel				
	Cold-rolled profile steel				
	Rolled stock total				
4	Welded tubing				
5	Non-ferrous metals:				
	Casting				
	Rolled brass				
	Rolled copper				
	Non-ferrous metals total				
6	Winding conductors:				
	Wire				
	Cable				
7	Bakelite tubing				
8	Bakelite cylinders				
9	Varnished fabric				
10	Pertinax				
11	Textolite				
12	Pressboard				
13	Transformer oil				
14	Lacquer				
15	Glyptal varnish				
16	Hard wood (beech)				
17	Rubber				
18	Miscellaneous				
	Total material costs				
	Total refuse, including:				
	reusable ferrous metals				
	reusable non-ferrous metals				
	Cost of materials minus cost of reusable refuse				
	Shipment and storage expenses				
	Total expenses				

Continued

Note. In view of the fact that the drawings give only the net weights of the parts and assemblies, their gross weight necessary for calculating the consumption of materials is found when multiplying the net weight by the following factors which allow for the refuse materials:

Materials	Factor
Electrical steel:	
transformers rated below 10,000 kVA	1.15
transformers rated above 10,000 kVA	1.2
Angle steel and channel bars	1.05
Sheet steel	1.1
Coiled steel	1.05
Steel piping	1.07
Pressboard and paper	1.1
Pertinax and textolite	1.1
Wood	3.0

Table 16.3

No.	Purchased standard items	Quantity	Price, rubles, copecks	Expenses per item
1				
2				
3				
.				
.				
10	Miscellaneous			
11	Shipment and storage expenses			
Total cost of purchased standard items				
Total cost of materials (from Table 16.2)				
Total cost of basic materials				

The total expenses on salaries and wages are determined from Table 16.4

Table 16.4

No.	Kinds of jobs	Time quota, hours	Rates
1	Assembly		
2	Winding and insulation operations: manufacture of windings manufacture of insulation		
3	Manufacture of core		
4	Welding		
5	Manufacture of equipment		
6	Machining and fastening		
7	Wood-working		
8	Electroplating		
9	Painting		
10	Casting		
11	Miscellaneous		
Total payment by piece rates			
Regular payment			
Total salaries and wages			

16.2. Calculation of Economic Effectiveness

The computation is made on the basis of annual expenses E_{an} .

The computation formula presented below is somewhat simplified to make understanding easier.

$$E_{an} = C_{an} + C_o P_o + C_{sc} P_{sc} + C_{var} Q_{var}$$

where $C_{an} = 0.185 \times \text{wholesale price} = \text{annual transformer cost}$

$P_o = \text{no-load losses, kW}$

$P_{sc} = \text{short-circuit losses, kW}$

$Q_{var} = \text{reactive power, kvar}$

The assumptions are:

$C_o = 50 \text{ rubles /kW} = \text{cost of 1 kW of no-load loss a year;}$

$C_{sc} = 25 \text{ rubles/kW} = \text{cost of 1 kW of short-circuit loss a year.}$

Expenses incurred for compensation of reactive power are equal to 1.5 rubles/kvar which gives the cost of 1 kvar of reactive loss a year.

The reactive power

$$Q_{var} = \frac{P}{100} \left(I_o \frac{8700}{8760} + V_l \frac{4000}{8760} \right)$$

where P = rated power, kVA

I_o = no-load current, %

V_l = reactive component of the impedance voltage, %

8760 = number of hours a year

8700 = number of hours a year for open-circuit losses

4000 = ditto, for short-circuit losses

Finally, the estimated formula for the calculation of annual losses is

$$E_{an} = 0.185 \times \text{wholesale price} + 50P_o + 25P_{sc} + \\ + 1.5 \frac{P}{100} \left(I_o \frac{8700}{8760} + V_l \frac{4000}{8760} \right) \text{ rubles per year}$$

When choosing the optimum version of the designed power transformer, the one with the least annual value of E_{an} will be the most economical.

Current Trends of Transformer Building in the USSR

Development and extension of electric power transmission lines is associated with a never-ending rise in voltages and powers of electrical machines and transformers. Recently, the line voltages of up to 500 kV have been brought into use. Supply of power at a voltage of 750 kV is under trial and theoretical design of systems rated at voltages as high as 1000 to 1200 kV capable of transmitting great powers over routes of 3000 to 4000 km long is under way (extending from powerful hydroelectric plants in Siberia to the European part of the USSR). Transformers of 417- and 630-MVA capacity are built in the Soviet Union and transformers of 800 and 1000 MVA are scheduled for production.

Development of transformer design commenced from the days of its invention. In the main, the transformer characteristics, weight and size parameters improved with the introduction of improved-quality and special-purpose materials. Thus, the use of alloy steel (starting in 1904) enabled the transformer weight to be reduced by nearly 50 per cent. At present, the quality of materials continues to be the governing factor in reducing the expenditure of ferromagnetic and conducting materials and in raising the transformer overall efficiency.

Power transformers possess a fairly high efficiency running to 98-99 per cent and even more in the majority of cases. However, the total losses in the entire transformer system amount to 6 per cent of the overall electric power generated by the power plants because the entire power capacity of transformers utilized in the distribution network is 7 to 8 times the capacity of generators.

The general national standard specifications now in force stipulate numerous improvements in design of power transformers as contrasted with the standards issued earlier. Primarily, this concerns the improvement of no-load and short-circuit parameters—important figures of merit through which a better efficiency is attained. The existing high level of efficiency became possible mainly due to the introduction of cold-rolled electrical steel which has smaller values of specific losses and reactive power as compared with hot-rolled steel. To utilize the properties of cold-rolled steel to the utmost, the transformer-building industry has had to look for more advanced engineering practices like elimination of slots in the core laminations, employment of the slot-free banding, use of mitre and combined (mitre and plain-butt) corner joints, special methods of annealing the laminations, utilization of non-metallic materials for longitudinal ducts, glass-fibre and glass-tape coverings, manufacture of coils without pre-stacking of the upper yoke, use of magnetic bridges and a variety of others.

Greater emphasis should be placed upon improvement of technology in the manufacture of windings and insulators, which are the vital and at the same time hard-to-control assemblies.

The pressboard is one of the most popular insulating materials and improvement of its quality is the problem at issue. The pressboard material that has been in use until now has the shrinkage of almost 8 or 9 per cent in thickness which calls for additional operations for adjustment of the insulation size.

The best solution would be the use of low-shrinkage pressboard, but so far it is not available and the transformer-building works have to resort to ageing of pressboard material and to pressure-clamping of windings at various stages of production.

As regards the large-size transformers, the manufacturers visualize the use of multiplex LV windings containing nearly 200 parallel conductors, HV lap windings with transposed conductors and individual tapped, multiplex layer HV windings with a number of voltage regulating steps corresponding to a number of layers. After drying, the windings are impregnated with oil-resistance varnishes and then baked

in order to improve their thermal conductivity and mechanical strength. It was established, however, that the electric strength of the impregnated windings drops by 10 to 15 per cent. This is why a good many manufacturers have given up the practice of impregnating windings rated at 110 kV and more. The desired mechanical strength of these windings may be achieved by applying axial compression with radial compaction in the process of winding, using the pressboard of improved hardness and low shrinkage, and also conductors with glyptal varnish placed over paper insulation, etc. A slightly decreased electric strength in the windings up to 35 kV is of minor importance and, therefore, impregnation holds good in these cases.

Of certain noticeable construction practices mention should be made of detachable and flared tanks, slip-on coolers made of straight pipes in place of tubular tanks, compressing rings wound from electrical steel strips and potted in epoxide resin.

The consumer's network efficiency and maintenance of constant supply voltages call for a more extensive manufacture of transformers with on-load voltage regulation. These transformers, whose power capacity will be brought to a 50 per cent of the total capacity of the power transformers produced, will include the majority of transformers rated at 110 kV and above, and also distribution transformers of 25 to 6300-kVA, 10 and 35 kV. These transformers should preferably employ the switchgear devices embodying the current-limiting resistors which have smaller sizes compared to the reactor devices and do not require a separate casing for contactors.

The concurrent development of power transformers with copper and aluminium windings will bring about greater saving of copper. This copper may be used in large transformers with a view to decreasing short-circuit losses at smaller sizes, which is unattainable in the case of aluminium windings. Transformers with copper and aluminium windings may display identical characteristics at the same weight of steel and lower total weight. However, the core height will be greater, leading, consequently, to a greater height of the entire transformer (reference 2). The power transformers with aluminium windings, having a power rating up

to 6300 kVA may serve as the counterparts of copper-wound transformers, as they can have similar no-load and short-circuit characteristics. The cost of these transformers is nearly the same and therefore this substitution may be regarded as fairly equivalent from the viewpoint of both technology and economy.

Economy in ferromagnetic, conducting, insulating and structural materials may be obtained primarily on account of a wider application of autotransformers rated at 110-500 kV due to a decrease in test voltages, reduction of insulation gaps in newly-designed insulators, use of new systems of forced cooling with a directional circulation of oil and introduction of new coolers.

The transformer size and reliable service are influenced by the quality of insulating materials and design of insulators, the more so in the case of increased voltages. The rational design, utilization of new and better materials, and introduction of advanced engineering practices help to reduce the insulation gaps and, eventually, to decrease the transformer size and weight.

It should be pointed out that introduction of electrostatic shielding protection effectively increased the transformer resistance to impulse effects. Nowadays this kind of overvoltage protection is being further perfected.

The expansion of transformer production, rise of unit power and increased voltages of HV windings necessitate more extensive investigation of leakage fields in order to find the ways of decreasing the extra losses, more comprehensive evaluation of a mechanical strength of short-circuited windings, electric strength of insulation at industrial frequency voltage and impulse surges, development of more effective cooling systems, more rational technology, for example, vacuum-drying of transformers, and efficient methods of transformer design.

Research greatly benefits the transformer-building plants in developing and manufacturing transformers consistent with the requirements of modern electrical engineering, such as, higher power capacities, service voltages and quality.

Chapter Eighteen

Course Design Projects

18.1. Assignment for Design Project of Oil-Cooled Power Transformer Rated at 3 to 35 kV

The minimum scope of assignment for the calculation of a power transformer is given in Sec. 2.1.

A complete calculation for determining optimum sizes and characteristics of the power transformer calls for a number of alternative calculations with different core diameters, which involves actually a fairly large scope of work. The student is not always able to do this work within the time allotted and therefore this work is made easier by supplementing the assignment with some reference data relieving the student from the task of choosing or precalculating them.

It is convenient to prepare the assignment on a special form, the sample of which is presented below.

Assignment No.—

for Course Design Project

Calculation of Three-Phase Power Transformer

Student (name) _____ Course _____ Group _____

Assignment issued _____ (date)

Project completed _____ (date)

Project accepted _____ (date)

Qualification mark _____

Assignment Data

Transformer capacity		kVA	
Open-circuit voltage		$\pm 5\%$	. . . V
Phasor group and type of connection			
Frequency		50 Hz	

Characteristics

Open-circuit losses	$P_o =$	W + 15%
Short-circuit losses	$P_{sc} =$	W + 10%
No-load current	$I_o =$	% + 30%
Impedance voltage	V_{sc}	% $\pm$ 10%

Additional Data

Core diameter, D	mm
Number of steps, n	
Yoke cross section	
Window height (approximate), H	mm
Steel	cold-rolled, 0.35 mm thick
Cooling	natural, oil
Instructor (name)	

18.2. Examples of Course Project Assignment

Case 1

Assignment Data

Transformer capacity	1000 kVA
Open-circuit voltage	$10,000 \pm 5\%$ / 400 V
Type of connection and phasor group	Y/∕ — 0
Frequency	50 Hz
Characteristics	as per Table 2.2

Additional Data

Core diameter	$D = 245$ mm
Number of steps	$n = 6$
Yoke cross section	two-stepped
Window height (approximate)	$H = 700$ mm
Steel	cold-rolled, varnished, 0.35 mm thick
Windings	copper
Cooling	natural, oil

Case 2

Assignment Data

Transformer capacity	2500 kVA
Open-circuit voltage	$35,000 \pm 2 \times$ $\times 2.5\%$ / 6900 V

Type of connection and phasor group	Y/ Δ — 11
Frequency	50 Hz
Characteristics	as per Table 2.2

Additional Data

Core diameter	$D = 300$ mm
Number of steps	$n = 7$
Yoke cross section	multi-step
Window height (approximate)	$H = 1000$ mm
Steel	cold-rolled, varnished, 0.35 mm thick
Windings	copper
Cooling	natural, oil

The appropriate sequence of calculation is presented in Sec. 18.3 below.

18.3. 1000-kVA, 10-kV Transformer

Core Calculation

Choice of core stack lamination sizes. By the assignment, the leg section is six-stepped whilst the yoke is two-stepped (Fig. 18.1).

Determine the width of laminations according to data given in Fig. 14.1. Choose the nearest normalized size yielding the best possible steel stamping:

$c_1 = 0.96 \times 245 = 235$ assumed to be equal to 230 mm

$c_2 = 0.885 \times 245 = 217$ assumed to be equal to 215 mm

$c_3 = 0.775 \times 245 = 190$ assumed to be equal to 195 mm

$c_4 = 0.632 \times 245 = 155$ assumed to be equal to 155 mm

$c_5 = 0.466 \times 245 = 114$ assumed to be equal to 120 mm

$c_6 = 0.28 \times 245 = 69$ assumed to be equal to 75 mm

Determine thickness b of the stacks so that the stepped figure could be inscribed in the circumference with diameter

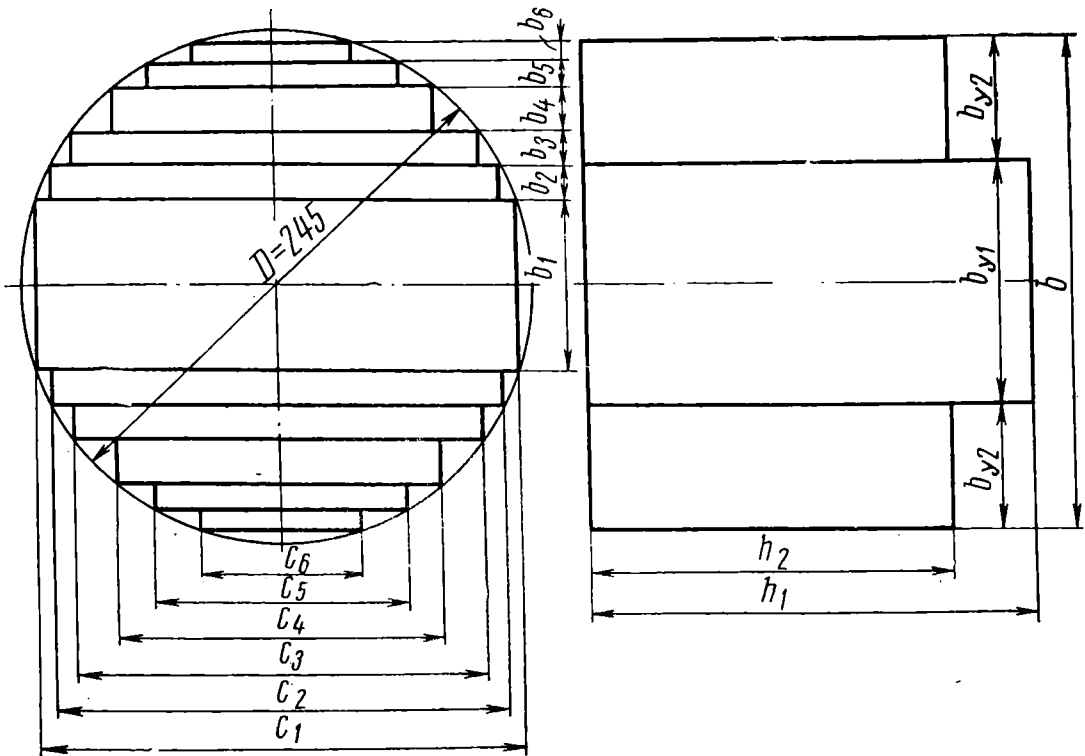


Fig. 18.1. Core leg and yoke cross sections

$D = 245$ mm. The calculation involved can be conveniently written as

$$b_1 = \sqrt{D^2 - c_1^2} = \sqrt{245^2 - 230^2} = 84 \text{ mm}$$

$$2b_2 = \sqrt{D^2 - c_2^2} - b_1 = \sqrt{245^2 - 215^2} - 84 = 34 \text{ mm}$$

$$2b_3 = \sqrt{D^2 - c_3^2} - (b_1 + 2b_2) = \sqrt{245^2 - 195^2} - 118 = 30 \text{ mm}$$

$$\begin{aligned} 2b_4 &= \sqrt{D^2 - c_4^2} - (b_1 + 2b_2 + 2b_3) = \\ &= \sqrt{245^2 - 155^2} - 148 = 42 \text{ mm} \end{aligned}$$

$$\begin{aligned} 2b_5 &= \sqrt{D^2 - c_5^2} - (b_1 + 2b_2 + 2b_3 + 2b_4) = \\ &= \sqrt{245^2 - 120^2} - 190 = 24 \text{ mm} \end{aligned}$$

$$\begin{aligned} 2b_6 &= \sqrt{D^2 - c_6^2} - (b_1 + 2b_2 + 2b_3 + 2b_4 + 2b_5) = \\ &= \sqrt{245^2 - 75^2} - 214 = 20 \text{ mm} \\ \hline b &= 234 \text{ mm} \end{aligned}$$

Next, determine the geometric and effective leg section and its two mid stacks (for the calculation of the weight of the leg corners, see below). Let space factor K_{sp} be 0.93, same as for steel sheets of 0.35 mm thick with single-layer varnish coating (refer to Table 11.1).

Determine the leg section:

$$\text{Stack 1 } 23.0 \times 8.4 = 193 \text{ cm}^2$$

$$\text{Stack 2 } 21.5 \times 3.4 = 73 \text{ cm}^2$$

$$\text{Stack 3 } 19.5 \times 3.0 = 58.5 \text{ cm}^2$$

$$\text{Stack 4 } 15.5 \times 4.2 = 65 \text{ cm}^2$$

$$\text{Stack 5 } 12.0 \times 2.4 = 28.8 \text{ cm}^2$$

$$\text{Stack 6 } 7.5 \times 2.0 = 15 \text{ cm}^2$$

$$A_{fig} = 433.3 \text{ cm}^2$$

$$A_{leg} = K_{sp} A_{fig} = 0.93 \times 433.3 = 403 \text{ cm}^2$$

$$A'_{leg} = 0.93 (193 + 73) = 247 \text{ cm}^2$$

Calculation of yoke section. The yoke section of a two-stepped form is usually reinforced, that is, its section should be approximately 5 per cent larger than the core section.

To determine the lamination width of the yoke mid-stack, i.e., its height h_1 , assume first that the yoke has a rectangular form with 15-per cent reinforcement.

$$h_1 = \frac{1.15 \times A_{fig}}{b} = \frac{1.15 \times 433.3}{234} = 21.3, \text{ rounded to } 21.5 \text{ cm}$$

The width of the laminations of extreme stacks of the yoke is about $0.8 h_1$, i.e., $h_2 = 0.8 \times 21.3 = 17.1$, rounded to 17.5 cm.

Determine the effective yoke section

$$\begin{aligned} A_y &= K_{sp} [(b_1 + 2b_2) h_1 + 2(b_3 + b_4 + b_5 + b_6) h_2] = \\ &= 0.93 [(8.4 + 3.4) 21.5 + (3.0 + 4.2 + 2.4 + 2.0) 17.5] = \\ &= 0.93 (254 + 203) = 425 \text{ cm}^2 \end{aligned}$$

The yoke reinforcement factor is

$$K_{rein} = \frac{A_y - A_{leg}}{A_{leg}} = \frac{425 - 403}{403} = 0.055 \text{ or } 5.5\%$$

Windings

Calculation of the number of turns of LV and HV windings. First find the value of volts per turn (e_N). Given induction $B = 1.7$ T, we have

$$e_N = 222 B A_{leg} \times 10^{-4} = 222 \times 1.7 \times 403 \times 10^{-4} = 15.2 \text{ V}$$

Then, determine the number of the LV winding turns. Note that in the case of a star connection $V_{ph} = V_{line} / \sqrt{3}$

$$N_{LV} = \frac{V_{ph LV}}{e_N} = \frac{V_{line LV}}{\sqrt{3} e_N} = \frac{400}{\sqrt{3} \times 15.2} = 15.2, \quad \text{rounded to 16 turns}$$

The number of the HV winding turns is determined on the basis of the phase voltage ratio

$$\begin{aligned} N_{HV} &= N_{LV} \frac{V_{ph HV}}{V_{ph LV}} = N_{LV} \frac{V_{line HV} \sqrt{3}}{V_{line LV} \sqrt{3}} = \\ &= 16 \frac{10,000}{400} = 400 \text{ turns} \end{aligned}$$

The number of the HV winding regulating turns (5%) is:

$$N_{reg} = 0.05 N_{HV} = 0.05 \times 400 = 20 \text{ turns}$$

Writing the number of turns on all the voltage steps gives

$$420 - 400 - 380/16 \text{ turns}$$

Verify induction in the leg and yoke because the number of turns in the LV winding has been rounded off to the whole number:

$$B_{leg} = \frac{V_{ph LV} \times 10^4}{N_{LV} \times 222 A_{leg}} = \frac{400 \times 10^4}{\sqrt{3} \times 16 \times 222 \times 403} = 1.615 \text{ teslas}$$

$$B_y = B_{leg} \frac{A_{leg}}{A_y} = 1.615 \frac{403}{425} = 1.53 \text{ teslas}$$

Calculation of phase currents through windings. In delta connection $I_{ph} = I_{line}$

$$I_{ph LV} = I_{line LV} = \frac{P \times 10^3}{\sqrt{3} \times V_{line LV}} = \frac{1000 \times 10^3}{\sqrt{3} \times 400} = 1445 \text{ A}$$

$$I_{ph HV} = I_{line HV} = \frac{P \times 10^3}{\sqrt{3} \times V_{line HV}} = \frac{1000 \times 10^3}{\sqrt{3} \times 10,000} = 57.7 \text{ A}$$

Calculation of LV winding (axial structure). A 1600-kVA transformer with service voltage of up to 690 V usually employs a double-layer, cylindrical LV winding although the version of a helical, duplex winding design is possible.

Version I. Double-layer, cylindrical winding. The current density is chosen within 4 to 4.5 A/mm².

The required conductor section is

$$s_c = \frac{I_{ph\ LV}}{\delta_{LV}} = \frac{1445}{4.5} = 321 \text{ mm}^2$$

Since there is no such section listed in Table 3.1, several parallel conductors should be chosen. Let us take a 12.5×5.6 -mm conductor with a cross section of 69.1 mm² and take five parallel conductors with a common cross section

$$s_c = 5 \times 69.1 = 345.5 \text{ mm}^2$$

Verify the current density

$$\delta_{LV} = \frac{1445}{345.5} = 4.18 \text{ A/mm}^2$$

Determine the axial size of the LV winding

$$\begin{aligned} H_{LV} &= (b + 0.59) n_c \left(\frac{N_{LV}}{2} + 1 \right) 1.03 = \\ &= (12.5 + 0.59) 5 \left(\frac{16}{2} + 1 \right) 1.03 = 605 \text{ mm} \end{aligned}$$

where $b = 12.5$ = axial size of conductor, mm

$n_c = 5$ = number of parallel conductors

1.03 = factor allowing for irregularity of wire laying

The radial size of the LV winding is

$$\begin{aligned} a_1 &= (a + 0.59 + 1) 2 + a_d = (5.6 + 0.59 + 1) 2 + 5 = \\ &= 19.4 \text{ mm} \end{aligned}$$

where $a = 5.6$ = radial size of wire, mm

1 = thickness of herringbone tape covering, mm

$a_d = 5$ = radial size of oil cooling duct, mm

Round a_1 to 20 mm.

Version II. Helical, duplex winding. Current density is chosen between 3.5 and 4 A/mm². The requisite cross section

of conductor

$$s_c = \frac{I_{ph LV}}{\delta_{LV}} = \frac{1445}{3.7} = 390 \text{ mm}^2$$

Determine the turn width

$$605 : (16 + 1) = 35.7 \text{ mm}$$

The winding is taken duplex on account of the large turn width (with ducts).

Select a 12.5×3.15 -mm conductor with a cross section of 38.8 mm^2 and take 10 parallel conductors.

Verify the current density

$$\delta_{LV} = \frac{1445}{10 \times 38.8} = 3.72 \text{ A/mm}^2$$

Axial winding structure

2 (16 + 1) conductors	$\times (12.5 + 0.59)$	= 445 mm
32 ducts	$\times 5$	= 160 mm
1 mid duct	$\times 10$	= 10 mm
		Total, 615 mm
		Compression = 10 mm
		Winding height = 605 mm

Compression comes to

$$\frac{10}{160 + 10} \times 100 = 5.9\%$$

Radial size of winding

$$a_1 = N_c (a + 0.59) 1.03 = 5 (3.15 + 0.59) 1.03 = 19.3 \text{ mm}$$

where $N_c = 5$ = number of parallel conductors in one group

$a = 3.15$ = radial size, mm

0.59 = two-sided thickness of insulation, mm

Take $a_1 = 19.5 \text{ mm}$.

Radial structure of the winding by two versions:

Version I	Version II
$D = 245 \text{ mm}$	$D = 245 \text{ mm}$
5 mm, duct	5 mm, duct
255 mm	255 mm
20 mm, LV _{wdg}	5 mm, cylinder

295 mm	265 mm
	6 mm, duct
	277 mm
	19.5 mm, LV _{wdg}
	316 mm

The correlation of both versions of the LV winding gives that the helical winding by version II is less efficient since it requires a greater cross section of conductors and occupies a larger radial space. Therefore, version I is accepted for further calculation of the LV winding.

Calculation of the HV winding (axial structure). The HV winding for the given power and voltage is taken to be continuous.

The current density is chosen between 3.5 and 4 A/mm².

The requisite cross section of conductor is

$$s_c = \frac{I_{ph\ HV}}{\delta_{HV}} = \frac{57.7}{3.7} = 15.6 \text{ mm}^2$$

Reasoning as in Sec. 3.4, we take 42 coils.

Then, the width of one coil plus duct (in axial direction) is $605 : 42 = 14.4 \text{ mm}$.

With a 6-mm duct the size of the insulated conductor is $14.4 - 6 = 8.4 \text{ mm}$.

Choose a conductor of $8 \times 2 \text{ mm}$ with a cross section of 15.6 mm^2 .

Verify the current density

$$\delta_{HV} = \frac{57.7}{15.6} = 3.7 \text{ A/mm}^2$$

Lay out the turns in the coils. 4 coils out of 42 (10%) are regulating and the others are main coils.

38 main coils $\times$ 10 turns	= 380 turns
4 regulating coils $\times$ 10 turns	= 40 turns
Total, 42 coils	420 turns

Calculation of axial structure

42 coils $\times$ 8.57 mm	= 360 mm
36 ducts $\times$ 6 mm	= 216 mm
1 enlarged mid duct $\times$ 12 mm	= 12 mm
4 end ducts $\times$ 8 mm	= 32 mm
Total,	620 mm

Compression of insulating spacers = 15 mm

Winding height = 605 mm

Compression of insulating spacers equals

$$\frac{15}{216 + 12 + 32} \times 100 = 5.8\%$$

which lies within tolerance limits (4 to 6%).

The radial size of the HV winding is

$$a_2 = N_t (a + 0.57) 1.03 = 10 (2 + 0.57) 1.03 = 26.5 \text{ mm}$$

where N_t = number of turns in coil

1.03 = factor allowing for irregularity of laying

Round a_2 to 27 mm.

The radial structure of the windings (initial):

$$\begin{array}{r} D = 245 \text{ mm} \\ \quad 5 \text{ mm, duct} \\ \quad 255 \text{ mm} \\ \quad 20 \text{ mm, LV}_{wdg} \\ \quad 295 \text{ mm} \\ \quad 17 \text{ mm, min. insulating gap} \\ \quad 329 \text{ mm} \\ \quad 27 \text{ mm, HV}_{wdg} \\ \hline 383 \text{ mm} \end{array}$$

The size of the main leakage path (17 mm) should be checked for compliance with the desired value of reactance drop, V_l .

To obtain the specified impedance voltage ($V_{sc} = 5.5\%$), the reactance drop should be

$$V_l = \sqrt{V_{sc}^2 - V_R^2} = \sqrt{5.5^2 - 1.22^2} = 5.36\%$$

$$\text{where } V_R = \frac{P_{sc}}{10 P} = \frac{12,200}{10 \times 1000} = 1.22\%.$$

Taking the additional leakage value as 5%, we should now obtain the reactance drop due to the main longitudinal field,

$$V'_l = \frac{V_l}{1.05} = \frac{5.36}{1.05} = 5.1\%$$

The reactance drop (denoted through V''_l) according to the initial calculation is

$$V''_l = \frac{IND_m \Delta K_R}{806 H_{wdg} e_N} = \frac{1445 \times 16 \times 31.2 \times 3.27 \times 0.966}{806 \times 60.5 \times 14.4} = 3.25\%$$

where $D_m = 29.5 + 1.7 = 31.2$, is the medium diameter of the main leakage path, cm

$\Delta = 1.7 + \frac{2+2.7}{3} = 3.27$, is the equivalent leakage path, cm

$$K_R = 1 - \frac{1.7+2+2.7}{\pi \times 60.5} = 0.966$$

$$e_N = \frac{400}{\sqrt{3} \times 16} = 14.4 \text{ V}$$

As the value V'_i is less than V''_i , the size of the main leakage path should be enlarged. The amount of enlargement may be approximately calculated by the formula

$$\begin{aligned} a' &= \left(\frac{V'_i}{V''} - 1 \right) \frac{D_m \Delta}{D_m + \Delta} = \\ &= \left(\frac{5.1}{3.25} - 1 \right) \times \\ &\times \frac{31.2 \times 3.27}{31.2 + 3.27} = 1.7 \text{ cm} \end{aligned}$$

Thus the width of the main path should be

$$a = 17 + 17 = 34 \text{ mm}$$

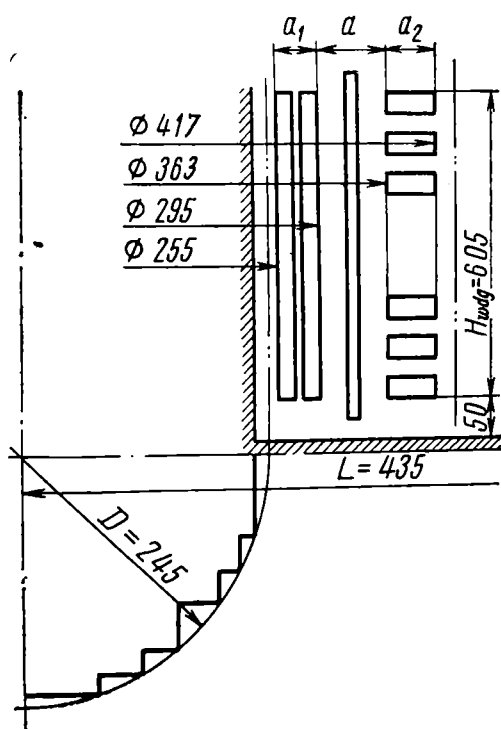


Fig. 18.2. Core and windings basic sizes resulting from the calculations

The final radial structure will be

- $D = 245$ mm
- 5 mm, duct
- 255 mm
- 20 mm, LV_{wdg}
- 295 mm
- 15 mm, duct
- 325 mm
- 5 mm, cylinder
- 335 mm

14 mm, duct
 363 mm
 27 mm, HV_{wdg}
 417 mm

18 mm is the spacing between HV windings of adjacent phases.

The length L between the limb centres is $417 + 18 = 435$ mm.

The height of the core window is equal to the height (length) of the winding H_{wdg} plus the insulation gaps to the yokes which are 50 mm for the given power and voltage:

$$H = H_{wdg} + 2 \times 50 = 605 + 100 = 705 \text{ mm}$$

Thus, we have obtained all the major sizes of the core and HV and LV windings schematically shown in Fig. 18.2.

Determination of Weight of Ferromagnetic and Conducting Materials

Weight of core legs

$$\begin{aligned} G_{legs} &= \gamma m A_{leg} H \times 10^{-3} = \\ &= 7.65 \times 3 \times 403 \times 70.5 \times 10^{-3} = 652 \text{ kg} \end{aligned}$$

Weight of yokes

$$\begin{aligned} G_y &= G_{y.str} + G_{y.c} = \gamma \times 4 A_y L \times 10^{-3} + \gamma \times 2 [A_{leg} h_2 + \\ &+ A'_{leg} (h_1 - h_2)] 10^{-3} = 7.65 \times 4 \times 425 \times 43.5 \times 10^{-3} + \\ &+ 7.65 \times 2 [403 \times 17.5 + 247 (21.5 - 17.5)] 10^{-3} = \\ &= 565 + 123 = 688 \text{ kg} \end{aligned}$$

where $G_{y.str}$ and $G_{y.c}$ = weight of the straight and corner parts of the yoke.

Total weight of electrical steel is

$$G_{st} = G_{legs} + G_y = 652 + 688 = 1340 \text{ kg}$$

Calculation of copper weight. For the LV winding,

$$\begin{aligned} G_{LV} &= m \pi \gamma s_c D_{LV} N_{LV} \times 10^{-6} = \\ &= 84 \times 345.5 \times 275 \times 16 \times 10^{-6} = 128 \text{ kg} \end{aligned}$$

For the HV winding,

$$G'_{HV} = 84 \times 15.6 \times 390 \times 420 \times 10^{-6} = 215 \text{ kg}$$

$$G''_{HV} = 84 \times 15.6 \times 390 \times 400 \times 10^{-6} = 205 \text{ kg}$$

(for calculation of short-circuit losses).

Total weight of copper

$$G_{Cu} = G_{LV} + G_{HV} = 128 + 215 = 343 \text{ kg}$$

Calculation of Characteristics

Calculation of open-circuit losses and no-load current.

The open-circuit losses,

$$\begin{aligned} P_o &= 1.1 [P_{leg} G_{leg} + P_y (G_{y.str} + K_{rein} G_{y.c})] = \\ &= 1.1 [1.37 \times 652 + 1.17 (565 + 1.5 \times 123)] = \\ &= 1.1 (894 + 878) = 1950 \text{ W} \end{aligned}$$

where $G_{y.str}$ = weight of the straight yoke portion.

Magnetizing current

$$\begin{aligned} I_{mag} &= \frac{Q_{leg} G_{leg} + Q_y G_y + N_j Q_{leg/j} A_{leg} + N_y Q_{y/j} A_y}{10P} = \\ &= \frac{7.1 \times 652 + 5.3 \times 688 + 3 \times 2.71 \times 403 + 4 \times 2.18 \times 425}{10 \times 1000} = 1.53\% \end{aligned}$$

The resistive component of no-load current

$$I_{oR} = \frac{P_o}{10P} = \frac{1950}{10 \times 1000} = 0.2\%$$

No-load current

$$I_o = \sqrt{I_{ol}^2 + I_{oR}^2} = \sqrt{1.53^2 + 0.2^2} \approx 1.55\%$$

Calculation of short-circuit losses. For the LV winding,

$$P_{sc LV} = 2.4 \delta_{LV}^2 G_{LV} K_{\Phi} = 2.4 \times 4.18^2 \times 128 \times 1.055 = 5650 \text{ W}$$

For the HV winding,

$$P_{sc HV} = 2.4 \times 3.72^2 \times 205 \times 1.02 = 6950 \text{ W}$$

Losses in the LV winding connection leads

$$P_{lead} = \frac{P}{100} \times \frac{I_{ph LV}}{100} = \frac{1000}{100} \times \frac{1445}{100} \approx 150 \text{ W}$$

Losses in the tank walls

$$P_t = 0.007 \times P^{1.5} = 0.007 \times 1000^{1.5} = 250 \text{ W}$$

Short-circuit losses

$$\begin{aligned} P_{sc} &= P_{sc \text{ LV}} + P_{sc \text{ HV}} + P_{lead} + P_t = \\ &= 5650 + 6950 + 150 + 250 = 13,000 \text{ W} \end{aligned}$$

Calculation of impedance voltage. The resistive component

$$V_R = \frac{P_{sc}}{10P} = \frac{13,000}{10 \times 1000} = 1.3\%$$

The reactive component

$$\Delta = 3.4 + \frac{2+2.7}{3} = 4.97 \text{ cm}$$

$$K_R = 1 - \frac{3.4+2+2.7}{\pi \times 60.5} = 0.958$$

$$V_l' = \frac{1445 \times 16 \times 32.9 \times 4.97 \times 0.958}{806 \times 60.5 \times 14.4} = 5.17\%$$

$$V_l = 1.05V_l' = 1.05 \times 5.17 = 5.43\%$$

Impedance voltage

$$V_{sc} = \sqrt{V_R^2 + V_l^2} = \sqrt{1.3^2 + 5.43^2} = 5.6\%$$

Calculation of voltage regulation.

(a) at $\cos \varphi_2 = 0.8$

$$\begin{aligned} \Delta V &= V_R \cos \varphi_2 + V_l \sin \varphi_2 + \frac{(V_l \cos \varphi_2 - V_R \sin \varphi_2)^2}{200} = \\ &= 1.3 \times 0.8 + 5.43 \times 0.6 = \frac{(5.43 \times 0.8 - 1.3 \times 0.6)^2}{200} = \\ &= 1.09 + 3.26 + 0.06 = 4.41\% \end{aligned}$$

(b) at $\cos \varphi_2 = 1$

$$\Delta V = V_R + \frac{V_l^2}{200} = 1.3 + 0.14 \approx 1.5\%$$

Calculation of efficiency:

(a) at $\cos \varphi_2 = 0.8$

$$\begin{aligned} \eta &= \left(1 - \frac{P_o + P_{sc}}{P \cos \varphi_2 \times 10^3 + P_o + P_{sc}} \right) 100 = \\ &= \left(1 - \frac{1950 + 13,000}{1000 \times 0.8 \times 10^3 + 1950 + 13,000} \right) 100 = 98.16\% \end{aligned}$$

(b) at $\cos \varphi_2 = 1$

$$\eta = \left(1 - \frac{1950 + 13,000}{1000 \times 10^3 + 1950 + 13,000} \right) 100 = 98.53\%$$

18.4. Calculation of Heat Flow of 1000-kVA Transformer

Calculation of temperature rise of LV winding. The cooling surface of a cylindrical double-layer winding is given by $A_{LV} = 3.5m\pi D_m H_{wdg} - 3mNcH_{wdg} = 3 \times 3.5 \times \pi \times 0.275 \times 0.605 - 3 \times 3 \times 8 \times 0.015 \times 0.605 = 5.48 - 0.65 = 4.83 \text{ m}^2$ where 3.5 = number of cooled surfaces of LV winding

m = number of phases (legs)

D_m = LV winding medium diameter, m

3 = number of surfaces covered with battens

n = number of battens

c = 0.015 = batten width, m

Specific heat load of the LV winding surface is

$$q_{LV} = \frac{P_{scLV}}{A_{LV}} = \frac{5650}{4.83} = 1170 \text{ W/m}^2$$

The temperature rise of the LV winding over oil temperature

$$\begin{aligned} \tau_{LV/oil} &= 0.159q_{LV}^{0.7} = 0.159 \times 1170^{0.7} = \\ &= 0.159 \times 140.5 = 22.4 \approx 23^\circ\text{C} \end{aligned}$$

The fractional exponents for q are given in Table 18.1 that follows

Table 18.1

Number q	$q^{0.6}$	$q^{0.7}$	$q^{0.8}$
300	—	—	95.9
400	—	—	120.7
500	41.6	77.5	144.3
600	46.4	88.0	166.9
700	50.9	98.1	188.8
800	55.2	107.7	—
900	59.1	116.9	—
1000	63.1	125.9	—
1100	66.8	134.6	—
1200	70.4	143.0	—
1300	73.9	151.3	—
1400	77.2	159.3	—
1500	80.5	167.2	—
1600	83.6	174.9	—
1700	86.75	182.5	—
1800	89.8	190.0	—
1900	92.75	197.3	—
2000	95.6	204.5	—

Calculation of temperature rise of HV winding. The covering factor showing how much the coils are fouled with spacers is

$$K_c = \frac{\pi D_m}{\pi D_m - nc} = \frac{\pi \times 390}{\pi \times 390 - 8 \times 40} = 1.35$$

where D_m = medium diameter of the HV winding, mm

n = number of spacers around the circumference

c = width of the spacer, mm

The perimeter of the coil section

$$p = 2(b_{ic} + a_2) = 2(8.57 + 27) = 71 \text{ mm}$$

Specific heat load of the HV winding

$$\begin{aligned} q_{HV} &= \frac{21.4N\delta K_c K_\Phi}{p} = \\ &= \frac{21.4 \times 57.7 \times 10 \times 3.72 \times 1.35 \times 1.02}{71} = 900 \text{ W/m}^2 \end{aligned}$$

The temperature rise of the HV winding over oil

$$\begin{aligned} \tau_{HV} &= 0.358 q_{HV}^{0.6} = 0.358 \times 900^{0.6} = \\ &= 0.358 \times 59.1 = 21.2 \approx 21.5^\circ\text{C} \end{aligned}$$

The temperature correction as a function of oil duct size (6×27 mm) is taken from Table 10.2

$$\Delta\tau_{wdg2} = K_d q_{HV} \times 10^{-3} = -3.3 \times 900 \times 10^{-3} = -3^\circ\text{C}$$

The final value of the HV winding temperature rise is $21.5 - 3 = 18.5^\circ\text{C}$

Calculation of oil temperature rise. Determine the size of the tank (see Fig. 10.10). The tank length

$$\begin{aligned} L_t &= 2L + D_{HV} = 2 \times 75 = 2 \times 435 + 413 + 2 \times 75 = \\ &= 1433 \approx 1440 \text{ mm} \end{aligned}$$

The tank width

$$B_t = D_{HV} + 2 \times 150 = 413 + 2 \times 150 = 713 \approx 720 \text{ mm}$$

The tank height

$$\begin{aligned} H_t &= H + 2h_y + h_{sp} + 50 = 705 + 2 \times 215 + 300 + \\ &+ 50 = 1485 \approx 1500 \text{ mm} \end{aligned}$$

The tank wall perimeter

$$p_t = \pi B_t + 2(L_t - B_t) = \pi \times 720 + \\ + 2(1440 - 720) = 3700 \text{ mm}$$

Tank side wall surface

$$A_t = p_t H_t = 3.7 \times 1.5 = 5.55 \text{ m}^2$$

Tank cover surface

$$A_{cover} = \frac{\pi}{4} B_t^2 + (L_t - B_t) B_t = \\ = \frac{\pi}{4} 0.72^2 + (1.44 - 0.72) 0.72 = 0.92 \text{ m}^2$$

To determine the requisite number of tubes, find the adequate multiplicity factor of the cooled surface (tank wall) as given in Table 10.4 (assuming that $q_t = 540 \text{ W/m}^2$)

$$K_{mult} = \frac{P_o \pm P_{sc}}{q_t A_t} = \frac{1950 + 13,000}{540 \times 5.55} = 5.0$$

Take three rows of tubes. The total effective surface of the tank is:

$$A_{t,eff} = K_{mult} A_t + 0.75 A_{cover} = 5.2 \times 3.7 \times 1.5 + \\ + 0.75 \times 0.92 = 29.6 \text{ m}^2$$

Specific heat load of the tank surface is

$$q_t = \frac{P_o + P_{sc}}{A_t} = \frac{14,950}{29.6} = 505 \text{ W/m}^2$$

The average temperature rise of oil

$$\tau_{oil} = 0.262 q_t^{0.8} = 262 \times 505^{0.8} = 0.262 \times 145.4 = 38.1^\circ\text{C}$$

Overheating of oil upper layers (with no correction introduced from Table 10.3)

$$\tau_{u,l} = 1.2 \tau_{oil} = 1.2 \times 38.1 = 45.7^\circ\text{C}$$

The height of the centre of losses

$$H_{loss} = \frac{1}{2} H + h_v + 50 = \frac{705}{2} + 215 + 50 = 617 \text{ mm}$$

The height of the centre of cooling

$$H_{cool} = \frac{1}{2} H_t = \frac{1500}{2} = 750 \text{ mm}$$

The losses-to-cooling height centre ratio

$$\frac{H_{loss}}{H_{cool}} = \frac{617}{750} = 0.825$$

The correction for the overheating of oil upper layers from Table 10.3

$$\Delta\tau_{oil} = 5.9^\circ\text{C}$$

Finally, the temperature rise of the upper layers of oil is

$$\tau_{u.l} = 45.7 + 5.9 = 51.6^\circ\text{C} < 55^\circ\text{C}$$

The temperature rise of the LV winding above the ambient

$$\tau_{LV} = \tau_{LV/oil} + \tau_{oil} = 23 + 38.1 = 61.1^\circ\text{C} < 65^\circ\text{C}$$

The temperature rise of the HV winding above the ambient

$$\tau_{HV} = \tau_{HV/oil} + \tau_{oil} = 18.5 + 38.1 = 56.6^\circ\text{C} < 65^\circ\text{C}$$

Thus, the calculated temperature rises of oil and windings are within permissible limits.

18.5. Calculation of Mechanical Stresses in Windings of 1000-kVA Transformer

The mechanical stresses are calculated by the formulae given in Sec. 7.4.

The maximum radial stress (acc. to 7.4) is:

$$\begin{aligned} F_{rad} &= 12.8 (IN)^2 \frac{\pi D_m}{H_{wdg}} \times 10^{-8} = \\ &= 12.8 (1445 \times 16)^2 \times \frac{\pi \times 33}{60.5} \times 10^{-8} = 117 \text{ kg} \end{aligned}$$

Similarly, in the case of a short-circuit (acc. to 7.5)

$$\begin{aligned} F_{rad.sc} &= F_{rad} K_m^2 \left(\frac{100}{V_{sc}} \right)^2 = 117 \times 1.455^2 \left(\frac{100}{5.5} \right)^2 = \\ &= 117 \times 700 = 82,000 \text{ kg} \end{aligned}$$

where K_m (coefficient allowing for DC component) =
 $= 1 + e^{-\frac{\pi V_R}{V_l}} = 1 + e^{-\frac{\pi \times 1.36}{5.43}} = 1.455$.

The axial stress inside the windings (acc. to 7.6)

$$F'_{ax} = F_{rad} \frac{\Delta}{2H_{wdg}} = 117 \frac{4.97}{2 \times 60.5} = 4.8 \text{ kg}$$

The axial stress due to the asymmetric distribution of magnetomotive forces along the winding height (acc Fig. 7.4 and formula 7.7) is

$$F''_{ax} = F_{rad} \frac{H_1}{H_l K_R m} = 117 \times \frac{6.4}{24.3 \times 0.96 \times 4} = 8 \text{ kg}$$

where $H_1 = 4 \times 8.5 + 3 \times 6 + 1 \times 12 = 64 \text{ mm} =$
 $= 6.4 \text{ cm}$ (on the 5% step)

$$H_l = \frac{B_t - b}{2} = \frac{72 - 23.4}{2} = 24.3 \text{ cm}$$

B_t = tank width, cm

b = core thickness, cm

K_R = Rogowski coefficient

$m = 4$

The total axial stress F_{ax} (for HV winding) is the sum of axial stresses F'_{ax} and F''_{ax} (acc. to 7.8)

$$F_{ax} = F'_{ax} + F''_{ax} = 4.8 + 8 = 12.8 \text{ kg}$$

In the case of a short circuit the axial stress rises in proportion with the square of short-circuit current, with allowance being made for the free current component:

$$F_{ax, sc} = 12.8 \times 700 = 8950 \text{ kg}$$

The bearing surface of the pressboard spacers in the HV winding

$$A_{sp} = nca_2 = 8 \times 4 \times 2.7 = 86 \text{ cm}^2$$

where n = number of spacers arranged around the circumference

c = spacer width; $c = 40 \text{ mm}$

a_2 = radial size of the HV winding

The maximum specific pressure on the spacers is

$$\sigma = \frac{F_{ax.sc}}{A_{sp}} = \frac{8950}{86} = 104 \text{ kg/cm}^2$$

which is quite permissible.

18.6. Electromagnetic Calculation of 2500-kVA, 35-kV Transformer

Calculation of Cores

Choosing the size of core leg stack laminations. For the given diameter $D = 300$ mm, with the number of steps $n = 7$, it is expedient to choose the normalized width sizes of the laminations accepted for use by transformer-building works. These sizes for the given core diameter are $c_1 = 295$; $c_2 = 270$; $c_3 = 250$; $c_4 = 230$; $c_5 = 215$; $c_6 = 175$; $c_7 = 135$ mm.

Determine the thickness of lamination stacks

$$b_1 = \sqrt{D^2 - c_1^2} = \sqrt{300^2 - 295^2} = 18 \text{ mm}$$

$$2b_2 = \sqrt{D^2 - c_2^2} - b_1 = \sqrt{300^2 - 270^2} - 18 = 112 \text{ mm}$$

$$2b_3 = \sqrt{D^2 - c_3^2} - (b_1 + 2b_2) = \sqrt{300^2 - 250^2} - 130 = 36 \text{ mm}$$

$$2b_4 = \sqrt{D^2 - c_4^2} - (b_1 + 2b_2 + 2b_3) = \sqrt{300^2 - 230^2} - 166 = 26 \text{ mm}$$

$$2b_5 = \sqrt{D^2 - c_5^2} - [b_1 + 2(b_2 + b_3 + b_4)] = \sqrt{300^2 - 215^2} - 192 = 16 \text{ mm}$$

$$2b_6 = \sqrt{D^2 - c_6^2} - [b_1 + 2(b_2 + b_3 + b_4 + b_5)] = \sqrt{300^2 - 175^2} - 208 = 36 \text{ mm}$$

$$2b_7 = \sqrt{D^2 - c_7^2} - [b_1 + 2(b_2 + b_3 + b_4 + b_5 + b_6)] = \sqrt{300^2 - 135^2} - 244 = 24 \text{ mm}$$

$$b = 268 \text{ mm}$$

Determine the leg cross section

$$\text{Stack 1 } 29.5 \times 1.8 = 53.1 \text{ cm}^2$$

$$\text{Stack 2 } 27.0 \times 11.2 = 302.5 \text{ cm}^2$$

$$\text{Stack 3 } 25.0 \times 3.6 = 90.0 \text{ cm}^2$$

$$\text{Stack 4 } 23.0 \times 2.6 = 59.8 \text{ cm}^2$$

$$\text{Stack 5 } 21.5 \times 1.6 = 34.4 \text{ cm}^2$$

$$\text{Stack 6 } 17.5 \times 3.6 = 63.0 \text{ cm}^2$$

$$\text{Stack 7 } 13.5 \times 2.4 = 32.4 \text{ cm}^2$$

$$A_{fig} = 635.2 \text{ cm}^2$$

$$A_{leg} = K_{sp} A_{fig} = 0.93 \times 635.2 = 590 \text{ cm}^2$$

Calculation of yoke cross section. The yoke cross section is assumed to be equal to the core cross section as regards its shape and sizes. Only the extreme (the 7th) stack of the yoke is of the same width as the 6th stack, which is done to facilitate the clamping of the yoke.

Thus, the active section of the yoke is

$$\begin{aligned} A_y &= K_{sp} [A_{fig} + (c_6 - c_7) 2b_7] = \\ &= 0.93 [635.2 + (17.5 - 13.5) 2.4] = 600 \text{ cm}^2 \end{aligned}$$

Calculation of Windings

First we shall find the value of volts per turn

$$e_N = 222 B A_{leg} \times 10^{-4} = 222 \times 1.7 \times 590 \times 10^{-4} = 22.3 \text{ V}$$

$V_{ph} = V_{line}$ when the LV winding is delta-connected.

Determine the number of turns for the LV winding:

$$N_{LV} = \frac{V_{ph LV}}{e_N} = \frac{V_{line LV}}{e_N} = \frac{6300}{22.3} = 282 \text{ turns}$$

$V_{ph} = \frac{V_{line}}{\sqrt{3}}$ on the HV side with the HV connected in star.

Therefore,

$$\begin{aligned} N_{HV} &= N_{LV} \frac{V_{ph HV}}{V_{ph LV}} = N_{LV} \frac{V_{line HV}}{\sqrt{3} V_{line LV}} = \\ &= 282 \frac{35,000}{\sqrt{3} \times 6300} = 904 \text{ turns} \end{aligned}$$

The number of turns of the voltage regulating step (2.5%) is

$$N_{reg} = 0.025 N_{HV} = 0.025 \times 904 = 22.6 \text{ turns}$$

Take 23 and 22 turns.

Writing the number of turns on all the voltage steps, we obtain: 959—927—904—881—859/282 turns.

Verify induction in the core leg and yoke:

$$B_{leg} = \frac{V_{ph LV} \times 10^4}{N_{LV} \times 222 A_{leg}} = \frac{6300 \times 10^4}{282 \times 222 \times 590} = 1.7 \text{ T}$$

$$B_y = B_{leg} \frac{A_{leg}}{A_y} = 1.7 \frac{590}{600} = 1.67 \text{ T}$$

Calculation of phase currents through windings. In the delta-connected LV winding, $I_{ph} = \frac{I_{line}}{\sqrt{3}}$

$$I_{ph LV} = \frac{I_{line LV}}{\sqrt{3}} = \frac{P \times 10^3}{\sqrt{3} \times \sqrt{3} V_{line LV}} = \frac{2500 \times 10^3}{3 \times 6300} = 132 \text{ A}$$

In the star-connected HV winding, $I_{ph} = I_{line}$

$$I_{ph HV} = I_{line HV} = \frac{P \times 10^3}{\sqrt{3} V_{line HV}} = \frac{2500 \times 10^3}{\sqrt{3} \times 3500} = 41.2 \text{ A}$$

Calculation of the LV winding (axial structure). For the given power capacity and service voltage, use is made of a continuous winding.

The current density is chosen between 3.5 and 4 A/mm². The requisite conductor section is

$$s_c = \frac{I_{ph LV}}{\delta_{LV}} = \frac{132}{3.8} = 34.7 \text{ mm}^2$$

Select a conductor 11.2 × 3.15 mm with a cross section of 34.7 mm².

Verify the current density:

$$\delta_{LV} = \frac{132}{34.7} = 3.8 \text{ A/mm}^2$$

The approximate winding height is

$$H_{wdg} = H - 2h_{y-wdg} = 1000 - 2 \times 75 = 850 \text{ mm}$$

where h_{y-wdg} is the yoke-to-winding height according to Table 13.4, equal to 75 mm.

The space needed for the wire and the duct (6 mm) is

$$11.2 + 0.59 + 6 = 17.79 \text{ mm}$$

The number of the winding coils is

$$850 : 17.79 \approx 48 \text{ coils}$$

Arrangement of turns in coils:

$$42 \text{ coils, 6 turns each} = 252 \text{ turns}$$

$$6 \text{ coils, 5 turns each} = 30 \text{ turns}$$

$$\text{All in all 48 coils} = 282 \text{ turns}$$

The winding axial structure:

$$48 \text{ coils} \times 11.79 \text{ mm} = 565 \text{ mm}$$

$$40 \text{ ducts} \times 6 \text{ mm} = 240 \text{ mm}$$

$$7 \text{ ducts} \times 5 \text{ mm} = 35 \text{ mm}$$

$$\text{Total,} \quad 840 \text{ mm}$$

$$\text{Compression} = 15 \text{ mm}$$

$$\text{Winding height } H_{wdg} = 825 \text{ mm}$$

Compression of spacers equals

$$\frac{15}{240 + 35} 100 = 5.5\%$$

Calculation of the HV continuous winding (axial structure). The requisite cross section of the wire

$$s_c = \frac{I_{ph \text{ HV}}}{\delta_{\text{HV}}} = \frac{41.2}{3.8} = 10.9 \text{ mm}^2$$

Select the conductor $6.3 \times 1.8 \text{ mm}$ with a cross section of 11 mm^2 .]

Verify the current density:

$$\delta_{\text{HV}} = \frac{41.2}{11} = 3.75 \text{ A/mm}^2$$

One conductor (coil) and one duct occupy axially

$$6.3 + 0.55 + 6 = 12.85 \text{ mm}$$

The number of coils in the winding is

$$825 : 12.85 = 64.2 \text{ (rounded to 66 coils)}$$

To ensure the voltage adjustment within $\pm 2 \times 2.5\%$ the number of regulating coils should be a multiple of four.

Therefore 58 main and 8 regulating coils should be chosen for the given case.

Arrangement of turns in coils:

47 coils, 15 turns each	= 705 turns
11 coils, 14 turns each	= 154 turns
Total,	859 main turns
6 coils, 11 turns each	= 66 turns
2 coils, 12 turns each	= 24 turns
Total,	90 regulating turns
Total,	66 coils, 949 turns

Axial structure:

66 coils $\times$ 6.85 mm	= 452 mm
64 ducts $\times$ 6 mm	= 384 mm
1 duct $\times$ 12 mm	= 12 mm
Total,	848 mm
Compression	= 23 mm
Winding height H_{wdg}	= 825 mm

Compression of the spacers is

$$\frac{23}{384 + 12} \times 100 = 5.8\%$$

The radial size of the LV winding is

$$a_1 = n_{coil}(a + 0.59) \times 1.03 = 6 \times (3.15 + 0.59) \times 1.03 = 23.1 \text{ mm}$$

Round a_1 to 24 mm.

The radial size of the HV winding is

$$a_2 = 15 \times (1.8 + 0.55) \times 1.03 = 36.3 \text{ mm, rounded to 37 mm}$$

The radial structure of the windings (initial)

D	= 300 mm
	= 5 mm, duct
	310 mm
	= 5 mm, cylinder
	320 mm
	= 8 mm, duct
	336 mm
	= 24 mm, LV_{wdg}
	384 mm
	= 27 mm, minimum insulation gap
	438 mm
	= 37 mm, HV_{wdg}
	512 mm

Check the main leakage path (27 mm) for the desired value of the reactance drop, with V_{sc} assumed to be 6.5%:

$$V_l = \sqrt{V_{sc}^2 - V_R^2} = \sqrt{6.5^2 - 0.94^2} = 6.44\%$$

where $V_R = \frac{P_{sc}}{10P} = \frac{23,500}{10 \times 2500} = 0.94\%$.

With an additional 5-per cent leakage, the reactance drop due to the main field is

$$V_l' = \frac{V_l}{1.05} = \frac{6.44}{1.05} = 6.13\%$$

The tentative value of the reactance drop is

$$V_l'' = \frac{IND_m \Delta K_R}{806 H_{wdg} h_{y-wdg}} = \frac{132 \times 282 \times 41.1 \times 4.73 \times 0.966}{806 \times 82.5 \times 22.3} = 4.7\%$$

where $D_m = 38.4 + 2.7 = 41.1$ cm

$$\Delta = 2.7 + \frac{2.4 + 3.7}{3} = 4.73 \text{ cm}$$

$$K_R = 1 - \frac{2.7 + 2.4 + 3.7}{\pi \times 82.5} = 0.966$$

As the obtained value V_l'' is less than V_l' , the size of the main path should be enlarged.

This enlargement is approximately calculated by the following formula:

$$a' = \left(\frac{V_l'}{V_l''} - 1 \right) \frac{D_m \Delta}{D_m + \Delta} = \left(\frac{6.13}{4.7} - 1 \right) \frac{41.1 \times 4.73}{41.1 + 4.73} = 1.3 \text{ cm}$$

That is, the width of the main path should be

$$a = 27 + 13 = 40 \text{ mm}$$

The final radial structure will be

$$\begin{aligned} D &= 300 \text{ mm} \\ &= 5 \text{ mm, duct} \\ &310 \text{ mm} \\ &= 5 \text{ mm, cylinder} \\ &320 \text{ mm} \\ &= 8 \text{ mm, duct} \\ &336 \text{ mm} \\ &= 24 \text{ mm, LV}_{wdg} \\ &384 \text{ mm} \\ &= 18 \text{ mm, duct} \\ &420 \text{ mm} \end{aligned}$$

$$\begin{array}{rcl}
 & = & 6 \text{ mm, cylinder} \\
 & & 432 \text{ mm} \\
 & = & 16 \text{ mm, duct} \\
 & & 464 \text{ mm} \\
 & = & 37 \text{ mm, HV}_{wdg} \\
 & & 538 \text{ mm} \\
 & & 32 \text{ mm (spacing between the} \\
 & & \text{windings of adjacent} \\
 & & \text{phases)} \\
 \hline
 & & 570 \text{ mm}
 \end{array}$$

The distance L between the axes of the legs is 570 mm. The height H of the core window is equal to the winding height H_{wdg} plus the insulation gaps h_{y-wdg} from the yoke to the winding, each being equal to 75 mm for the given power and voltage:

$$H = H_{wdg} + 2 \times 75 = 825 + 150 = 975 \text{ mm}$$

Thus, we have determined the basic sizes of the core and the HV and LV windings.

Determination of Weight of the Ferromagnetic and Conducting Materials

It is good practice to determine the weight of steel with regard to the mid (axial) line of the leg and yoke cross sections, provided that the yoke section follows the cross section of the leg. The length of the extreme legs and yokes may be taken from the middle of the corner (Fig. 18.3). The mid leg length may be taken as H plus the elongation of stacks from the 2nd to the penultimate stack.

Weight of the core legs

$$\begin{aligned}
 G_{legs} = & \gamma A_{leg} (3H + 2c_1) 10^{-3} + \gamma [2b_2c_2(c_1 - c_2) + \\
 & + 2b_3c_3(c_1 - c_3) + 2b_4c_4(c_1 - c_4) + 2b_5c_5(c_1 - c_5) + \\
 & - 2b_6c_6(c_1 - c_6) + 2b_7c_7(c_1 - c_6)] 10^{-3}
 \end{aligned}$$

Determine the weight termwise:

$$\begin{array}{rcl}
 7.65 \times 590 (3 \times 97.5 + 2 \times 29.5) 10^{-3} & = & 1590 \text{ kg} \\
 7.65 \times 11.2 \times 27 (29.5 - 27) 10^{-3} & = & 6 \text{ kg} \\
 7.65 \times 3.6 \times 25 (29.5 - 25) 10^{-3} & = & 3 \text{ kg} \\
 7.65 \times 2.6 \times 23 (29.5 - 23) 10^{-3} & = & 3 \text{ kg} \\
 7.65 \times 1.6 \times 21.5 (29.5 - 21.5) 10^{-3} & = & 2 \text{ kg} \\
 7.65 \times 3.6 \times 17.5 (29.5 - 17.5) 10^{-3} & = & 6 \text{ kg} \\
 7.65 \times 2.4 \times 13.5 (29.5 - 17.5) 10^{-3} & = & 3 \text{ kg}
 \end{array}$$

$$G_{legs} = 1613 \text{ kg}$$

The weight of yokes

$$G_y = \gamma A_y \times 4L \times 10^{-3} = 7.65 \times 600 \times 4 \times 57 \times 10^{-3} = 1050 \text{ kg}$$

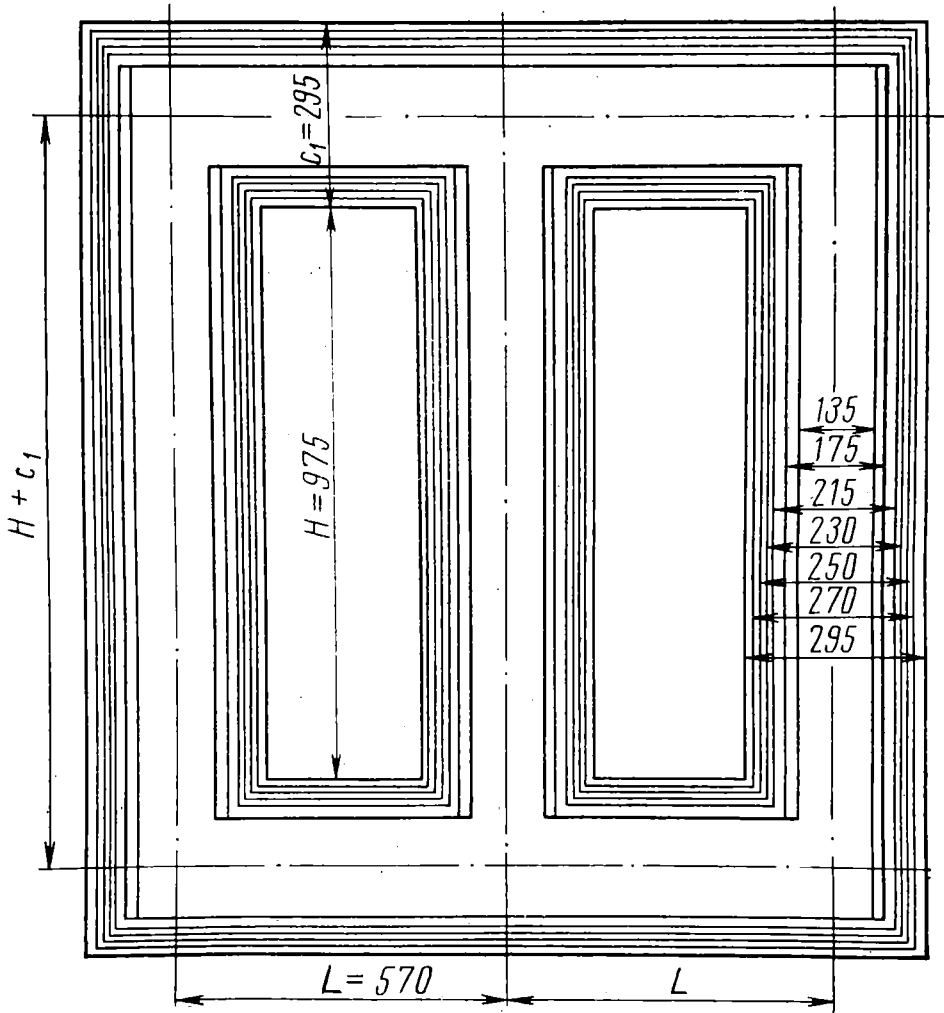


Fig. 18.3. Determining the length of legs and yokes (with stepped yokes)

The weight of the yoke and leg corners

$$\begin{aligned} G_c &= G_{leg.c} + G_{y.c} = \gamma A_{leg} \times 2c_1 + \gamma A_y \times 2c_1 = \\ &= 7.65 \times 590 \times 2 \times 29.5 \times 10^{-3} + 7.65 \times 600 \times 2 \times 29.5 \times \\ &\quad \times 10^{-3} = 266 + 271 = 537 \text{ kg} \end{aligned}$$

The total weight of electrical steel

$$G_{st} = G_{legs} + G_y = 1613 + 1050 = 2663 \text{ kg}$$

Calculation of copper weight. For the LV winding,

$$\begin{aligned} G_{LV} &= m\gamma\pi s_c D_{LV} N_{LV} \times 10^{-6} = \\ &= 84 \times 34.7 \times 360 \times 282 \times 10^{-6} = 296 \text{ kg} \end{aligned}$$

For the HV winding,

$$G_{HV} = 84 \times 11 \times 501 \times 949 \times 10^{-6} = 440 \text{ kg}$$

$$G'_{HV} = 84 \times 11 \times 501 \times 904 \times 10^{-6} = 418 \text{ kg (for calculation of short-circuit losses)}$$

Total weight of copper,

$$G_{cu} = G_{LV} + G_{HV} = 296 + 440 = 736 \text{ kg}$$

Calculation of Transformer Characteristics

Calculation of open-circuit losses and no-load current.

The open-circuit losses

$$\begin{aligned} P_o &= 1.1P_{leg} [G_{leg} + (K_{reinf} - 1) G_{leg.c}] + \\ &+ 1.1P_y [G_y + (K_{reinf} - 1) G_{y.c}] = 1.1 \times 1.6 (1613 + \\ &+ 0.5 \times 266) + 1.1 \times 1.52 (1050 + 0.5 \times 271) = \\ &= 3070 + 1980 = 5050 \text{ W} \end{aligned}$$

Magnetizing current

$$\begin{aligned} I_{mag} &= \frac{Q_{leg} G_{leg} + Q_y G_y + N_j Q_{leg/j} A_{leg} + N_y Q_{y/j} A_y}{10P} = \\ &= \frac{8.8 \times 1613 + 8.2 \times 1050 + 3 \times 3.26 \times 590 + 4 \times 3.06 \times 600}{10 \times 2500} = \\ &= 1.44\% \end{aligned}$$

The no-load current resistive component

$$I_{o.R} = \frac{P_o}{10P} = \frac{5050}{10 \times 2500} = 0.2\%$$

No-load current

$$I_o = \sqrt{I_{o.mag}^2 + I_{o.R}^2} = \sqrt{1.44^2 + 0.2^2} = 1.45\%$$

Calculation of short-circuit losses. For the LV winding,

$$P_{sc LV} = 2.48_{LV}^2 G_{LV} K_{\Phi} = 2.4 \times 3.82^2 \times 296 \times 1.03 = 10,600 \text{ W}$$

For the HV winding,

$$P_{sc\ HV} = 2.4 \times 3.75^2 \times 418 \times 1.02 = 14,400\text{ W}$$

Losses in the LV winding connection leads

$$P_{lead} = \frac{P}{100} \times \frac{I_{ph\ LV}}{100} = \frac{2500}{100} \times \frac{132}{100} = 33\text{ W (taken as 50 W)}$$

Tank wall losses

$$P_t = 0.007 \times P^{1.5} = 0.007 \times 2500^{1.5} = 875 \approx 900\text{ W}$$

Short-circuit losses

$$\begin{aligned} P_{sc} &= P_{sc\ LV} + P_{sc\ HV} + P_{lead} + P_t = \\ &= 10,600 + 14,400 + 50 + 900 = 25,950\text{ W} \end{aligned}$$

Calculation of impedance voltage. The resistive component is

$$V_R = \frac{P_{sc}}{10P} = \frac{25,950}{10 \times 2500} = 1.04\%$$

The reactive component

$$\Delta = 4 + \frac{2.4 + 3.7}{3} = 6.03\text{ cm}$$

$$K_R = 1 - \frac{4 + 2.4 + 3.7}{\pi \times 82.5} = 0.961$$

$$V_i' = \frac{132 \times 282 \times 42.4 \times 6 \times 0.961}{806 \times 82.5 \times 22.3} = 6.17\%$$

$$V_i = 1.05V_i' = 1.05 \times 6.13 = 6.48\%$$

Impedance voltage

$$V_{sc} = \sqrt{V_R^2 + V_i^2} = \sqrt{1.05^2 + 6.48^2} = 6.5\%$$

Calculation of voltage regulation

(a) at $\cos \varphi_2 = 0.8$

$$\begin{aligned} \Delta V &= 1.04 \times 0.8 + 6.48 \times 0.6 + \frac{(6.48 \times 0.8 - 1.04 \times 0.6)^2}{200} = \\ &= 0.84 + 3.86 + 0.1 = 4.8\% \end{aligned}$$

(b) at $\cos \varphi_2 = 1$

$$\Delta V = 1.04 + \frac{6.48^2}{200} = 1.25\%$$

Calculation of efficiency(a) at $\cos \varphi_2 = 0.8$

$$\eta = \left(1 - \frac{5050 + 25,950}{2500 \times 0.8 \times 10^3 + 5050 + 25,950} \right) 100 = 98.47\%$$

(b) at $\cos \varphi_2 = 1$

$$\eta = \left(1 - \frac{5050 + 25,950}{2500 \times 10^3 + 5050 + 25,950} \right) 100 = 98.77\%$$

18.7. Calculation of Heat Flow of 2500-kVA Transformer

Calculation of LV winding temperature rise. The factor accounting for the covering of the coil surface with spacers is

$$K_c = \frac{\pi D_m}{\pi D_m - nc} = \frac{\pi \times 360}{\pi \times 360 - 8 \times 40} = 1.4$$

The coil cross section perimeter

$$p = 2(a_1 + b_{ic}) = 2(24 + 11.8) = 71.6 \text{ mm}$$

The specific heat load of the LV winding surface

$$q_{LV} = \frac{21.4 I N \delta K_c K_\Phi}{P} = \frac{21.4 \times 132 \times 6 \times 3.8 \times 1.4 \times 1.03}{71.6} = 1300 \text{ V/m}^2$$

The temperature rise of the winding over oil

$$\tau_{LV} = 0.41 q_{LV}^{0.6} = 0.41 \times 1300^{0.6} = 0.41 \times 73.9 = 30.3^\circ\text{C}$$

Correction for the temperature rise as a function of oil duct size (6×24) is taken from Table 10.2

$$\Delta \tau_{wdg 2} = K_{duct} q_{LV} \times 10^{-3} = -3.9 \times 1300 \times 10^{-3} = 5.1^\circ\text{C}$$

The final value of the LV winding temperature rise

$$30.3 - 5.1 = 25.2^\circ\text{C}$$

Calculation of the HV winding temperature rise. The factor of covering the winding with spacers

$$K_c = \frac{\pi \times 501}{\pi \times 501 - 8 \times 40} = 1.26$$

The coil section perimeter

$$p = 2(6.85 + 37) = 87.7 \text{ mm}$$

The specific heat load of the HV winding

$$q_{HV} = \frac{21.4 \times 41.2 \times 15 \times 3.75 \times 1.26 \times 1.02}{87.7} = 730 \text{ W/m}^2$$

The temperature rise of the winding over oil

$$\tau_{HV} = 0.358 \times 730^{0.6} = 0.358 \times 52.2 = 18.7^\circ\text{C}$$

The correction for overheating is taken from Table 10.2

$$\Delta\tau_{wdg2} = -2.2 \times 730 = -1.6^\circ\text{C}$$

The final value of the HV winding temperature rise is

$$18.7 - 1.6 = 17.1^\circ\text{C}$$

Calculation of oil temperature rise. Determine the tank size:

The tank length

$$L_t = 2L + D_{HV} + 2 \times 75 = 2 \times 570 + 538 + \\ + 2 \times 75 = 1828 \approx 1850 \text{ mm}$$

The tank width

$$B_t = D_{HV} + 2 \times 150 = 570 + 2 \times 150 = 870 \text{ mm}$$

The tank height

$$H_{wdg} = H + 2c_1 + h_{sp} + 50 = 975 + 2 \times 295 + \\ + 470 + 50 = 2085 \text{ mm}$$

In view of the fact that the transformers with the given power employ radiator tanks, the minimum tank height should be taken from Table 10.6, i.e. 2225 mm.

The tank wall perimeter

$$p_t = \pi B_t + 2(L_t - B_t) = \pi \times 870 + \\ + 2(1850 - 870) = 4690 \text{ mm}$$

The tank wall surface

$$A_t = p_t H_t = 4.69 \times 2.225 = 10.4 \text{ m}^2$$

The tank cover surface

$$A_{cover} = \frac{\pi}{4} B_t^2 + (L_t - B_t) B_t = \frac{\pi}{4} 0.87^2 + \\ + (1.85 - 0.87) 0.87 = 1.44 \text{ m}^2$$

Determine the required cooling surface:

$$A_{cool} = \frac{P_o + P_{sc}}{q_t} = \frac{5050 + 25,950}{540} = 57.5 \text{ m}^2$$

The requisite radiator surface

$$\begin{aligned} A_{rad} &= A_{cool} - A_t - 0.75A_{cover} = \\ &= 57.5 - 10.4 - 0.75 \times 1.44 = 46 \text{ m}^2 \end{aligned}$$

Take five ordinary radiators 188/9.4.

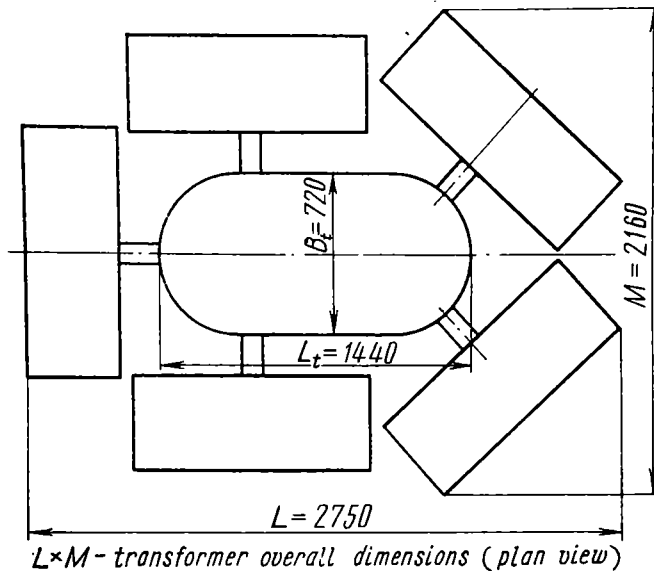


Fig. 18.4. Arrangement of radiators on the tank of 2500-kVA transformer

Use the data given in Fig. 10.13 and check the arrangement of radiators on the tank wall (Fig. 18.4).

The total effective surface of cooling

$$A'_{eff} = 10.4 + 5 \times 9.45 + 1.08 = 59.7 \text{ m}^2$$

The specific heat load of the tank surface

$$q_t = \frac{P_o + P_{sc}}{A'_{eff}} = \frac{31,000}{59.7} = 520 \text{ W/m}^2$$

The mean temperature rise of oil

$$\tau_{oil} = 0.262 \times q_t^{0.8} = 0.262 \times 520^{0.8} = 0.262 \times 149 = 39^\circ\text{C}$$

The temperature rise of the upper oil layers (with no correction introduced from Table 10.3)

$$\tau_{u.l} = 1.2\tau_{oil} = 1.2 \times \overset{39}{46.8} = 39^\circ\text{C } 46.8^\circ\text{C}.$$

The height of the centre of losses

$$H_{loss} = \frac{1}{2}H + h_y + 50 = \frac{1}{2}975 + 295 + 50 = 832.5 \text{ mm}$$

The height of the centre of cooling

$$H_{cool} = \frac{1}{2}H_t = \frac{2225}{2} = 1112.5 \text{ mm}$$

Loss-to-cooling height centre ratio is

$$\frac{H_{loss}}{H_{cool}} = \frac{832.5}{1112.5} = 0.75$$

The correction for the overheating of oil upper layers (taken from Table 10.3) is

$$\Delta\tau_{oil} = 4.5^\circ\text{C}$$

Finally, the temperature rise of the oil upper layers is

$$\tau_{u.l} = 46.8 + 4.5 = 51.3 < 55^\circ\text{C}$$

The temperature rise of the LV winding above the ambient

$$\tau_{LV} = \tau_{LV/oil} + \tau_{oil} = 25.2 + 39 = 64.2^\circ\text{C} < 65^\circ\text{C}$$

The temperature rise of the HV winding over the ambient

$$\tau_{HV} = \tau_{HV/oil} + \tau_{oil} = 17.1 + 39 = 56.1^\circ\text{C} < 65^\circ\text{C}$$

The calculated temperature rises of oil and windings do not go beyond the specified tolerances.

18.8. Calculation of Mechanical Stresses in the Windings of 2500-kVA Transformer

The maximum radial stress (acc. 7.4)

$$\begin{aligned} F_{rad} &= 12.8(IN)^2 \frac{\pi D_m}{H_{wdg}} 10^{-8} = 12.8 (132 \times 282)^2 \times \\ &\times \frac{\pi \times 42.4}{82.5} 10^{-8} = 285 \text{ kg} \end{aligned}$$

Similarly, in the case of a short circuit (7.5),

$$F_{rad.sc} = F_{rad} K_m^2 \left(\frac{100}{V_{sc}} \right)^2 = 285 \times 1.6^2 \left(\frac{100}{6.5} \right)^2 = 285 \times 606 = 173,000 \text{ kg}$$

where $K_m = 1 + e^{-\frac{\pi \times 1.04}{6.48}} = 1.6$.

The axial stress inside the windings (7.6)

$$F'_{ax} = F_{rad} \frac{\Delta}{2H_{wdg}} = 285 \frac{6.03}{2 \times 82.5} = 10.4 \text{ kg}$$

The axial stress due to the asymmetric distribution of the magnetomotive forces along the winding height (7.7) is

$$F''_{ax} = F_{rad} \frac{H_1}{H_l K_{Rm}} = 285 \frac{10.9}{30.1 \times 0.961 \times 4} = 26.8 \text{ kg}$$

where $H_1 = 8 \times 6.85 + 7 \times 6 + 1 \times 12 = 109 \text{ mm}$ (on the 5% step).

$$H_l = \frac{B_t - b}{2} = \frac{87 - 26.8}{2} = 30.1 \text{ mm}$$

The total axial stress F_{ax} (for the HV winding) is the sum of axial stresses F'_{ax} and F''_{ax} (7.8)

$$F_{ax} = F'_{ax} + F''_{ax} = 10.4 + 26.8 = 37.2 \text{ kg}$$

In the case of a short circuit the axial stress rises in proportion with the square of short-circuit current, the direct current component being allowed for

$$F_{ax.sc} = 37.2 \times 606 = 22,700 \text{ kg}$$

The bearing surface of the pressboard spacers in the HV winding

$$A_{sp} = n c_2 a_2 = 8 \times 4 \times 3.7 = 118 \text{ cm}^2$$

The maximum specific pressure upon the spacers

$$\sigma = \frac{F_{ax.sc}}{A_{sp}} = \frac{22,700}{118} = 192 \text{ kg/cm}^2, \text{ which is permissible.}$$

18.9. Graphical Representation of the Course Design Project

Apart from the calculations, the scope of the course design project envisages making the drawings of the core (frame), HV and LV windings, and the basic units of the transformer.

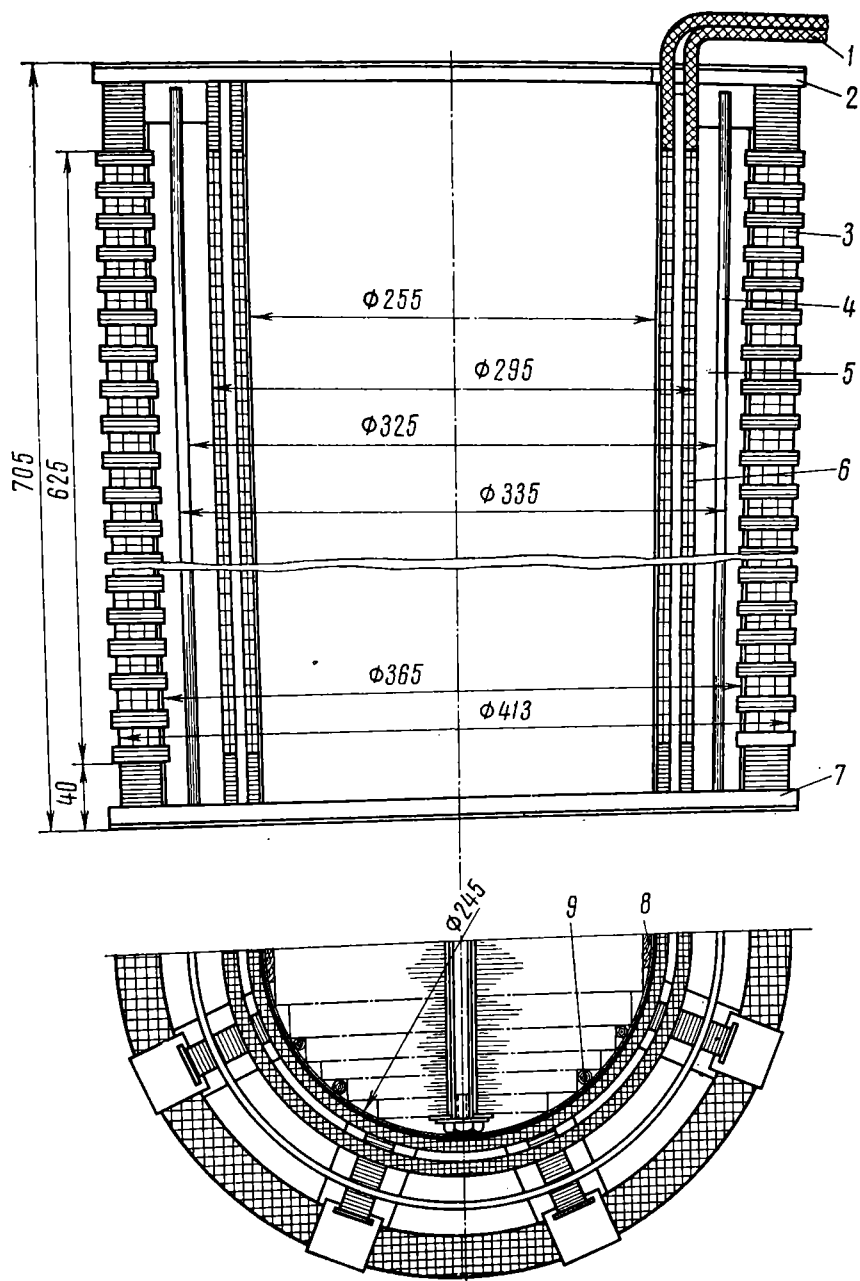
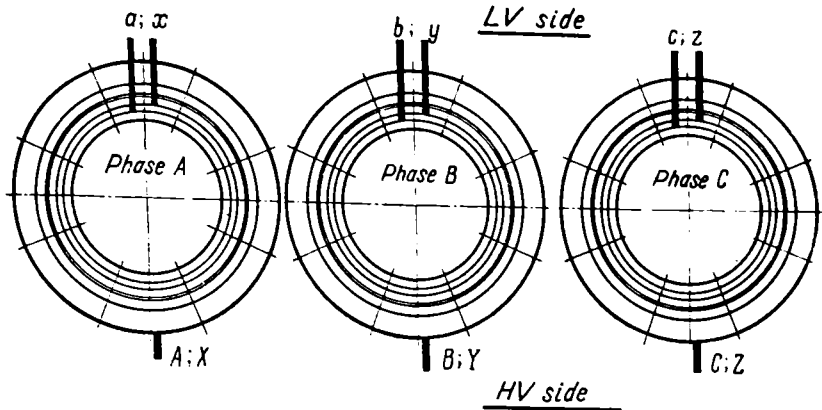
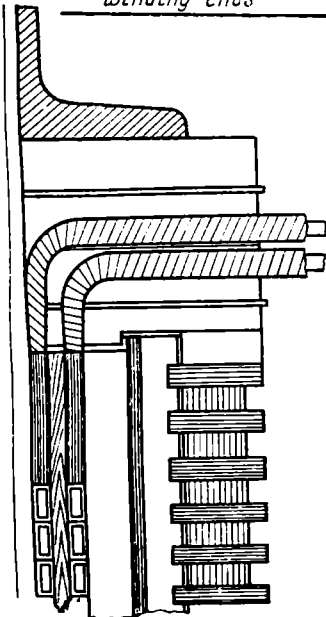


Fig. 18.5. Arrangement of windings

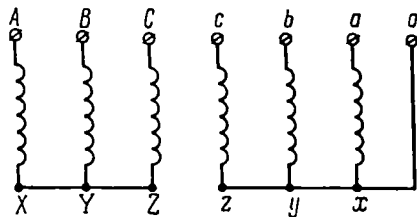
Location of winding ends



Arrangement of LV winding ends



Y/Y₀-0 connection diagram



9	Rod	24	Red beech wood
8	Plate	6	Red beech wood
7	Yoke insulation	3	Pressboard
6	Winding	3	Set
5	Batten	24	Pressboard
4	Cylinder	3	Bakelite
3	Winding	3	Set
2	Yoke insulation	3	Pressboard
1	Tape		Taffeta tape
Ref. Name	Qty		Material
COURSE DESIGN PROJECT			
Attachment of Windings (1000/10-transformer)			

in 1000-kVA, 10-kV transformer

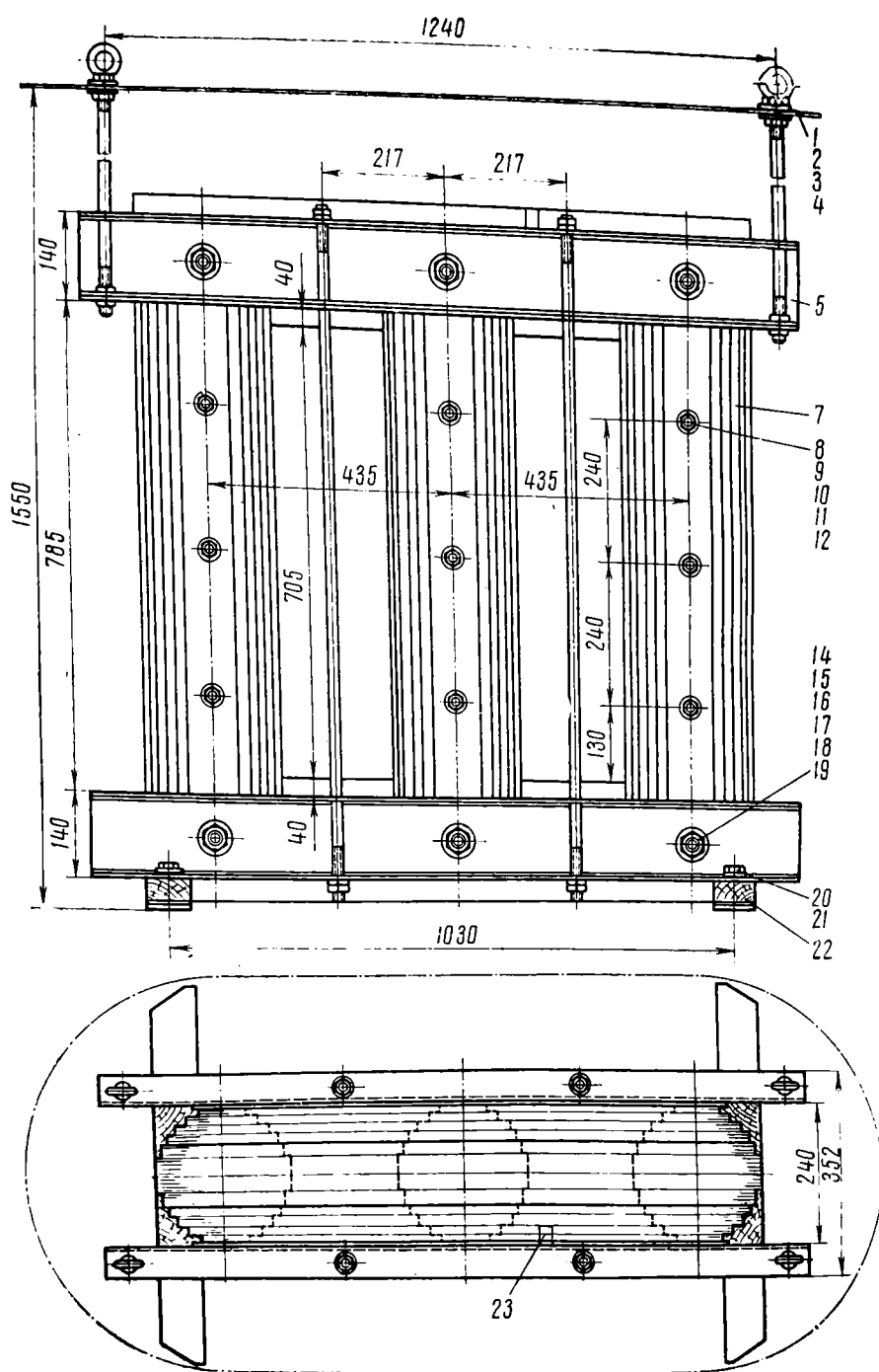
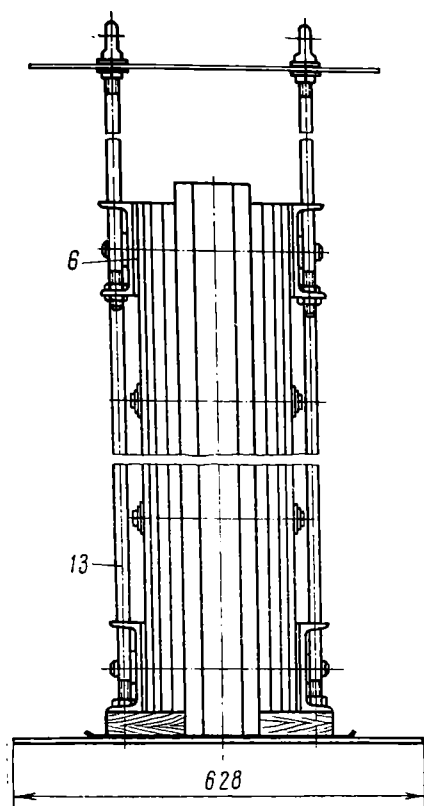
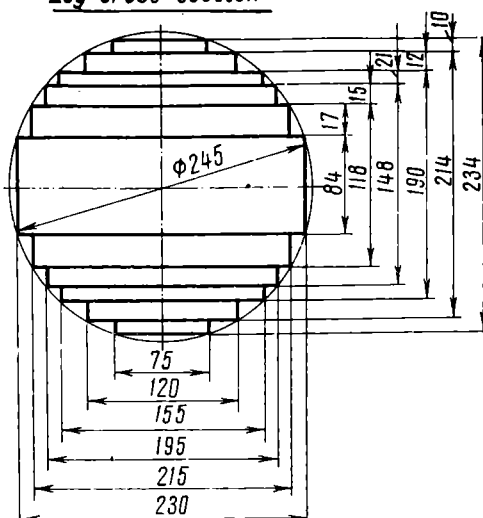


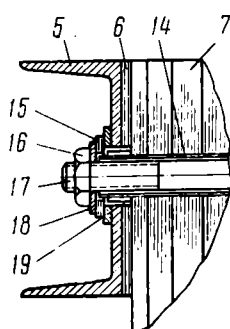
Fig. 18.6. Frame of 1000-kVA.



Leg cross section



Yoke clamping



23	Earthing	1	Copper
22	Bar	4	Red beech wood
21	Washer	4	Steel
20	Bolt	4	Steel
19	Tube	6	Bakelite
18	Washer	12	Steel
17	Pin	6	Steel
16	Nut	12	Steel
15	Spacer	12	Pressboard
14	Tube	6	Bakelite
13	Pin	4	Steel
12	Tube	9	Bakelite
11	Spacer	18	Pressboard
10	Washer	18	Steel
9	Nut	18	Steel
8	Pin	9	Steel
7	Core	1	Steel
6	Spacer	4	Pressboard
5	Yoke beam	4	Steel
4	Pin	4	Steel
3	Nut	28	Steel
2	Washer	8	Steel
1	Lifting ring	4	Steel
Ref.	Name	Qty	Material

COURSE DESIGN PROJECT

Frame (1000/10-transformer)

10-kV transformer

The drawing of the frame should consist of at least two projections of the frame and separately drawn sections of the core leg and yoke with the indicated clamping elements.

The drawing of the winding set should be done in two projections of the LV and HV windings fitted one into the other, indicating the fasteners securing the windings on the leg and the support insulation on the yokes. Besides, the drawing should have a sectional view of the arrangement of LV winding ends, and also a winding connection diagram. It is also desirable to draft individual details, for example, a transition point and its insulation in the continuous winding, etc.

Both the drawings should be made strictly to the machine-building drawing rules, with the scales observed and the specifications properly filled in.

By way of illustration, Fig. 18.5 and Fig. 18.6 show the teaching drawings of the frame and winding set of the 1000-kVA, 10-kV transformer, made according to the project assignment given in Sec. 18.2.

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Index

- Air gap, effect of, 183
- Autotransformers, 105-110
 - capacity of, 107
 - economy factor of, 107
 - regulating, 109
 - three-winding, 109, 110, 111
- Battens, 190, 191, 198-200
- Buchholz (gas) relays, 242-244
- Bushing insulator, porcelain, 246-249
- Circuits
 - polyphase, 123
 - six-phase, rectification, 125-127
 - three-phase, magnetic, 178, 179
- Coils, 18
- Connections
 - delta, 38-40
 - star, 38-40
 - zigzag, 37
- Connection groups, 35, 38, 108
(*see also* Phasor groups)
- Conservator, oil, 207, 241, 242
- Cooling, 25, 30, 151
 - air, 152
 - air-blast, 165
 - oil, 152, 165
- Coolers, 170, 171
- Core
 - butt-joint, 20, 21, 180, 181
 - calculation of, 284, 301
 - diameter of, 45
 - interleaved, 20, 21, 181, 182
 - magnetic, 20, 41
 - size of, 40-43
 - weight of, 47, 293, 307, 388
- Creepage distance, 225, 247, 248
- Current
 - DC, use of, 11
 - circulating, 141
 - magnetizing, 63
 - no-load, 35-37, 59-62, 66, 180
 - no-load, calculation of, 294, 309
 - short-circuit, 145
- Current density, 51, 57, 58, 256
- Ducts, cooling, 58, 155, 156, 159, 160, 162, 227
- Efficiency, 27, 91-95, 118, 119
 - calculation of, 295, 311
- Filters
 - oil siphon, 246
 - reactor, 131
 - smoothing, 131
- Flux
 - apparent, 76, 77
 - leakage, 19, 65, 67, 72, 75, 77, 98, 103, 117
 - magnetic, 19, 65, 69, 79
- Flux density, 46, 47, 51
- Flux linkage, 78, 79
- Gaps, insulation, 222, 224-226
- Geneva drive, 141, 142

Heat

convection of, 156, 157
dissipation of, 155-157
effect of, 147, 150
radiation of, 152, 157

Impedance voltage, 33, 36, 69,
71, 82, 115-117

calculation of, 295, 310

Induction, electromagnetic, 17,
65, 66

Insulation, 27, 131, 205

external, 205

internal, 205

strength of, 206

Joints

butt, 21, 64, 180

interleaved, 181, 182

mitre, 176, 185

Leakage path, 75-78, 81, 102, 115,
291, 306

Load demand, 14, 15, 92, 94

Losses

copper, 60, 71, 95, 130

core, 60, 61

eddy-current, 20, 60

open-circuit, 35, 59-62, 70, 92,
93

open-circuit, calculation of,
294, 309

extra, 60, 71-73, 160

short-circuit, 35, 69-71, 82,
92, 93, 115

short-circuit, calculation of,
294, 309, 310

Mechanical stresses, calculation
of, 299, 314, 315

Overvoltages, 205, 210

Phasor groups and diagrams, 38,
40, 67, 83, 86, 111, 127, 263

Power, reactive, 61, 63, 64

Protection

capacitive shielding, 215

lightning, 193, 214, 215

overvoltage, 186, 205

Reactor, current-limiting, 138,
143, 147

Reactor, neutralizing, 127

Rectifiers, 122, 123, 129

Regulation, voltage, 51, 55, 85,
118, 133, 138

calculation of, 295, 310

output characteristic of, 90-91

Resistor, current-limiting, 143,
145-147

Space factor, 45, 47, 176, 177, 286

Switches, 135, 250-254

Tank, 24, 25, 139, 157, 164-166,
170, 237-240

calculation of, 297, 312

Tap changing, 96, 133

off-circuit, 133-136, 250, 251

on-load, 134, 136-137, 142-146

Tap changer, 136-138

Temperature detector, 245

Temperature rise, 152, 154-158,
163, 172, 256

calculation of, 296-298, 311,
312

Tests

acceptance, 154, 257

applied-potential, 208, 209,
258, 259

final, 260

induced-potential, 207, 209,
258, 259

insulation, 207, 261, 262

leakage, 267

open-circuit, 59, 258, 262, 263

proof, 259

short-circuit, 71, 82, 258, 263,
264

voltage withstand, 206, 210

Thermometer, mercury, 244, 245

- Transformation ratio, 20, 36, 37
60, 106, 114, 133, 143
- Transformer
air-cooled, 205
classification of, 29
core-type, 177, 178
history of, 13
installation of, 268, 269
mechanical stresses in, 100
off-load tap-changing, 36
oil-immersed, 164
on-load tap-changing, 36
rectifier, 124
safety in use of, 269
shell-type, 110, 148, 177, 178
single-phase, 38, 177
step-down, 14
step-up, 14
three-phase, 21, 39, 40, 50, 66, 117, 180
three-winding, 112-115, 117
type designation of, 30, 31
- Transformer cost, 137, 229, 274, 281, 355
- Transformer materials, 26
- Transpositions, 196, 199, 201, 203
- Voltage drops
- inductance, 69-71
reactance, 76, 77, 94-99, 100, 115, 116
resistance, 69-71
- Voltage regulator, 136, 148
- Windings
axial size of, 53
calculation of, 287-293, 302
concentric, 23, 223
continuous, 51, 55, 160, 195, 198, 237, 290, 304
cylindrical, layer, 53, 159, 188, 190, 191, 220, 221, 288
disc, 162, 188, 195, 196
duplex, 53, 198, 202
height of, 53-55
helical, 51, 53, 55, 160, 223, 288
lap, 216
sandwich, 23, 24, 223
simplex, 53, 198
- Yoke, 22, 46, 49
calculation of, 286, 302, 303

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